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GEOLOGY AND MINERAL RESOURCES OF THE SINKING SPRING QUADRANGLE, BERKS AND LANCASTER COUNTIES, PENNSYLVANIA

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COMMONWEALTH OF PENNSYLVANIA
DEPARTMENT OF ENVIRONMENTAL RESOURCES
BUREAU OF
TOPOGRAPHIC AND GEOLOGIC SURVEY
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ATLAS 177d

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PREFACE

Atlas 177d presents a detailed discussion of the geology and mineral resources of the Sinking Spring quadrangle, a 58 square mile area west of Reading, Pennsylvania, based on information gathered in the field and in the laboratory. Included within this report are data on the rock units, their composition, structure and geologic history. The unconsolidated, surficial sediments also have been dealt with as the need for information about these materials is steadily growing.

Today, as the land and its resources are increasingly being used by man and concern for proper planning and management of the land is being demonstrated, the information provided in this report is of direct use to planners, developers, engineers, industry and the public. Specific attention is given to meet these needs in the form of data on environmental and engineering characteristics of the rocks, including ground water potential and possible mineral resources within this area. This report provides broad, basic information and data applicable to a wide variety of interests and needs; for certain site-specific projects it may be desirable to call upon professional consultants.

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GEOLOGY AND MINERAL RESOURCES OF THE SINKING SPRING QUADRANGLE, BERKS AND LANCASTER COUNTIES, PENNSYLVANIA

by

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TRACY V. BUCKWALTER

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ABSTRACT

The map area lies west of the City of Reading and comprises approximately 58.5 sq. miles in four geologically and topographically distinct terrains in the Great Valley and Piedmont provinces. This report treats areal geology, stratigraphy and structure of Cambrian, Ordovician and Triassic sedimentary rocks, petrography of Precambrian and Triassic crystalline rocks, their mineral resources and environmental geology. A complex structural evolution is traced wherein the upper limb of the Lebanon Valley nappe has been identified for the first time, and a new Irish Mountain nappe is defined which includes crystalline rocks of the northwestern Reading Prong in its core.

The southern third of the quadrangle is in the Newark-Gettysburg basin which is here filled with fluvial conglomerates and finer red sediments of the Triassic Hammer Creek Formation and the Morgantown diabase sheet. The northern margin of the basin is at least partially defined by faulting, but the Wheatfield inlier of Paleozoic rocks suggests that such faulting is only one component in evolution of the basin. Horizontal slickensides and folding of the Triassic sediments as well as regional tilting into the basal unconformity require an active post-depositional history which is not fully understood. Overall trend of the basin is clearly related to inherited structural grain, and some evidence shows that the margin in this area may have been initially defined by a late Paleozoic reverse fault.

Hills of lower Cambrian quartzite and Precambrian gneiss, discontinuously present north of the Triassic basin, bear a clear affinity to the Reading Prong. The older gneisses are clearly of sedimentary origin but are much invaded and replaced by later granitic gneiss. These hills are rootless and are emplaced as a late Paleozoic thrust sheet apparently derived from the core of the Taconic age Lebanon Valley nappe.

A second late Paleozoic thrust sheet containing Cambrian carbonates derived from the upper limb of the Lebanon Valley nappe lies beneath the gneiss and quartzite hills and extends across the quadrangle. East of the transverse fault near Wernersville this thrust plate lies on Ordovician carbonates of the upper limb of the Irish Mountain nappe with stratigraphic affinities to the Lehigh Valley sequence. To the west equivalent carbonates of the lower limb of the Lebanon Valley nappe are superposed on the Irish Mountain nappe beneath the later thrust.

Second order complexities place several patches of Ordovician shale within the carbonates of the central part of the map area, but a variety of shales and some associated coarser-grained rocks and thin-bedded limestones characteristically form hills in the northern quarter of the area. A portion of these shales was evidently initially deposited on the carbonate rocks and properly belongs to the Martinsburg Formation. A major part, however, is not typical autochthonous Martinsburg lithology and some of it is as old as some of the carbonate rocks. These rocks should be excluded from the Martinsburg Formation and are here placed in an informal Hamburg sequence, recognizing that they are characteristic of the Hamburg "klippe" of Stose. The Hamburg sequence rocks were evidently gravitationally displaced prior to or early in development of the carbonate and crystalline nappes and represent an early phase of the Taconic orogeny.

There is a history of iron mining in the quadrangle but there appears to be no significant remaining quantity of magnetite ore associated with the Morgantown diabase and the spotty limonite deposits of the carbonate rocks have had no economic potential for a long time. Geochemical indications of other metals are negative except possibly aluminum which might ultimately be recovered from aluminous (over 19% $A1_20_3$) shale of the Hamburg sequence.

Ganister and silica brick were formerly produced from the Hardyston quartzite which presently yields building sand and some aggregate. Some brick is produced from shales in the area, and there is potential for other clay products including lightweight aggregate. A wide variety of building stones have been used at least locally and a potential market for a good brownstone and black "granite" from the Triassic rocks might still be developed.

Carbonate rocks are quarried for aggregate, some agricultural stone, and related uses. These currently do, and should continue to, provide a major economic resource. Preservation of stone lands for future production should be considered in regional planning. Large reserves of carbonate rocks are available, but none meet current standards for metallurgical or other uses for which chemical composition is critical.

Land use varies considerably among the geologically distinct areas owing to differences in topography, water availability, soil fertility, and related factors. Geologic environment factors are considered with stress on engineering characteristics which should be evaluated with respect to sinkholes and cavernous carbonate rock.

INTRODUCTION

LOCATION

The Sinking Spring 7½-minute quadrangle is located west of the city of Reading, Pennsylvania, and lies mostly within Berks County with the southwest portion extending into Lancaster County (Figure 1). It is defined by the limits of 40°15′ to 40°22′30″ north latitude and 76°00′ to 76°07′30″ west longitude. It is bounded to the north by the Bernville-quadrangle, to the east by the Reading quadrangle, to the south by the Terre Hill quadrangle, and to the west by the Womelsdorf quadrangle (Pa. Geol. Survey, 4th ser., Atlas 177c, 1963).

SURFACE FEATURES AND PHYSIOGRAPHIC PROVINCES

The project area is crossed roughly from east to west by four subequal belts characterized by distinctive topography and land use which represent portions of widely recognized physiographic and geologic provinces.

The northern belt is dominated by moderate size hills with local relief not exceeding 200 feet. Bottomlands of larger streams are not extensive but are commonly cultivated. They are usually flanked by fairly steep slopes, ordinarily in pasture or woodland. Above the valleys, extensive interfluves have more moderate slopes. This area is largely cultivated, though substantial portions have been relegated to permanent pastures or entirely abandoned in recent years. Cultivation of forage crops and orchards and dairying appear to be the principal activities. These hills are underlain primarily by shale or its slightly metamorphosed equivalents which weather into arable but not especially rich soils in which weathered shale chips are usually more or less conspicuous.

To the south, the shale terrane drops somewhat abruptly to a gently rolling, carbonate-floored valley. This area is intensively cultivated with a variety of crops and also contains the larger communities and principal manufacturing industries in the area. The valley, an easy route for east-west commerce, is used by the Reading Railroad and U. S. Route 422. Permanent streams in the carbonate valley are not abundant; and with the exception of a few large springs, they are largely fed from adjacent uplands. Despite lower mean elevation, the western part of the valley is drained northward across the shale into Tulpehocken Creek. The major portion of the carbonate valley is generally drained northeasterly, somewhat oblique to the valley trend, by Cacoosing Creek and its tributaries. Only a bit of the southeastern portion is drained in the obvious direction, eastward to the nearby Schuylkill River. Soils are generally clay loams with usually sparse carbonate, quartz and chert fragments, except on the southern side of the valley where quartzite and gneiss fragments of colluvial origin from hills to the south become increasingly more abundant and coarser southward. The colluvial deposits do not generally appear to

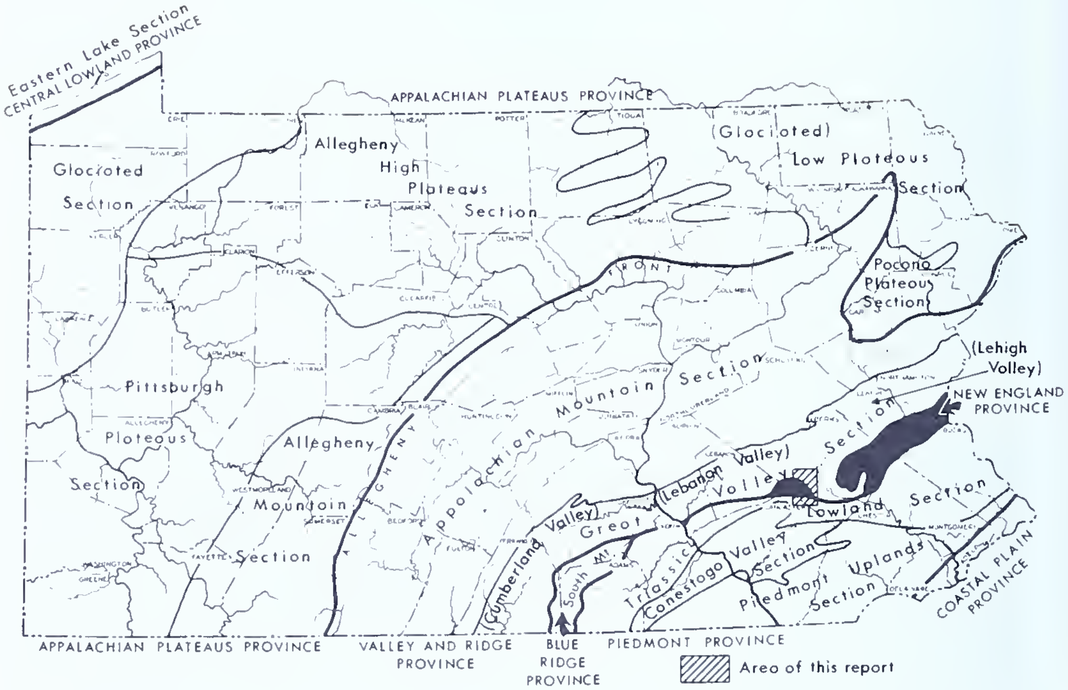

Figure 1. Physiographic provinces of Pennsylvania and location of area of this report. Reading Prong of New England Province and its extension in South Mountain shown in black.

be very thick, at least toward the west, where occasional outcrops of carbonate are found close to parent rocks of the colluvium. The hills demarking the south side of the valley (Figure 3) are notably higher and steeper than the shale margin to the north (Figure 2).

The shale and carbonate belts jointly lie in the Great Valley Section of the Valley and Ridge Physiographic Province. Regionally, this province is characterized by moderately strongly to quite strongly deformed, negligibly to slightly metamorphosed sedimentary rocks of Paleozoic age. The Great Valley is the southeasternmost valley developed on erosionally less resistant rocks of the Paleozoic deposits and is floored by the very thick carbonate and shale section of Cambrian and Ordovician age. The longitudinal subdivision of the Great Valley by the carbonate-shale contact is regionally pervasive.

Basal clastics of the Paleozoic section are an obvious stratigraphic entity of the rocks of the Valley and Ridge Province, but their geologic behavior has been similar to the ancient metamorphic rocks on which they were deposited. They are accordingly placed in a distinct province of which the ancient gneisses are a characteristic element. The discontinuous belt of such quartzite and gneiss, which forms hills rising steeply to as much as 800 feet above the carbonates on the south side of the valley, is obviously the distal extension of the Reading Prong of the New England Province by geologic affinities. Regional physiographers using primarily topographic criteria, however, have often included these isolated fragments in the adjacent and related Piedmont Physiographic Province to simplify delimitation of provincial boundaries. Rest homes, camps, and resorts compose a significant portion of the total habitations. The prevalent steep slopes commonly have thin, rocky soil and are largely in woodland. There is no obvious difference in the character or use of the land whether the bedrock is quartzite or gneiss.

The southern belt of Triassic rocks is irregularly hilly in some parts and gently rolling in others. Elevations range from 400 to 1,060 feet above sea level. A few distinct ridges mark the outcrop of the most resistant conglomerates. Laurel Ridge is the most prominent of these. Over much of the area the hills appear somewhat chaotic, though some strike lines can be distinguished, especially in the southeastern part of the quadrangle. The highest hill, southeast of Camp Indiandale, is formed by resistant conglomerate members and contains the axis of a plunging syncline. Adamstown Ridge, at the southern edge of the quadrangle, is formed by resistant sandstone with prominent conglomerate members. Some hills with elevations of 700 to 800 feet are underlain by resistant diabase.

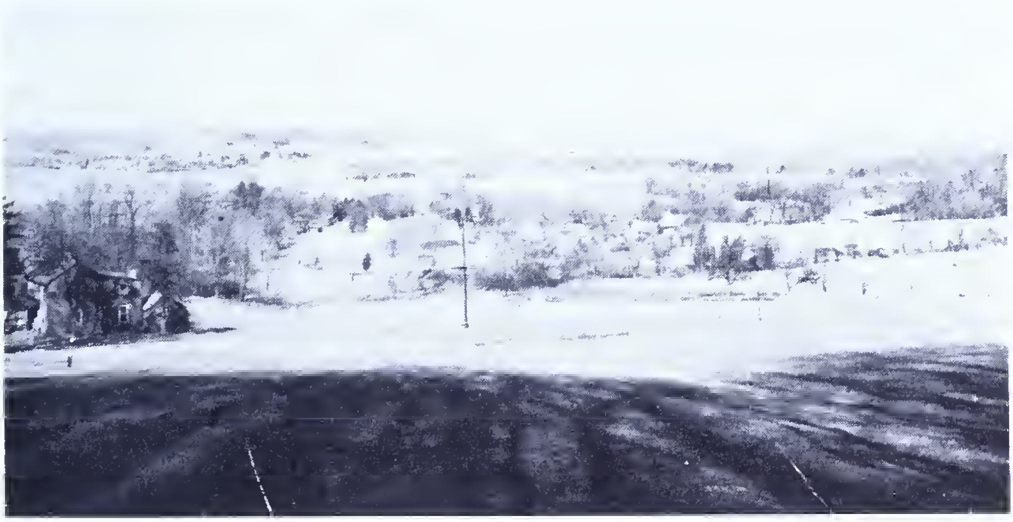

Figure 2. View north across limestone valley. Shale escarpment in middle distance. Blue Mountain of Silurian quartzite dimly visible on horizon.

The general character of the landscape and land-use patterns is intermediate between those of the northern shale belt and the quartzite-gneiss belt. About 40 percent of the area is in woodland, generally in the hilly areas. The more rolling areas are cleared and generally under cultivation, although the soil is generally of low natural fertility. Land use in the cleared areas is about the same as in the northern shale belt, and it does not seem to be influenced by changes in character of the Triassic bedrock.

The area of Triassic rocks lies in the Newark-Gettysburg Basin which is physiographically classed as part of the Triassic Lowland Section of the Piedmont Province.

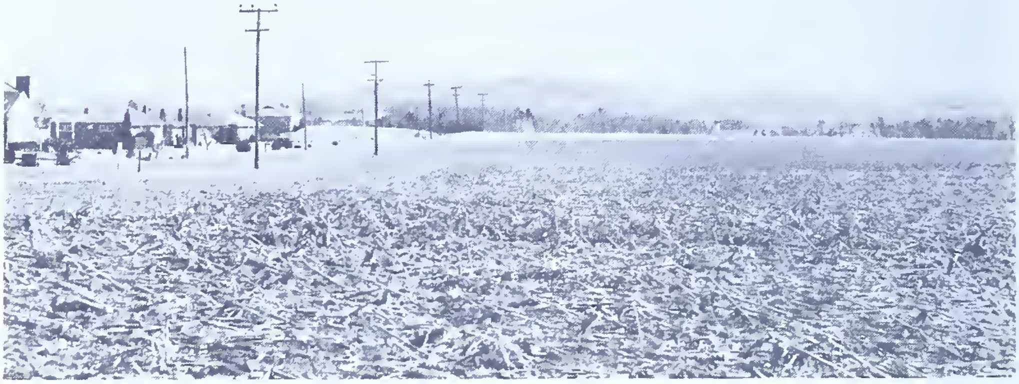

Figure 3. View south in limestone valley to hills of quartzite and gneiss.

A major drainage divide between flow northward to Tulpehocken Creek and on eastward to the Schuylkill River, and flow southward to Connestoga Creek on westward to the Susquehanna River, generally follows the crest of quartzite-gneiss ridge. The discontinuity in the quartzite at Olive Leaf Chapel, however, gives the headwaters of Cacoosing Creek access to the south; and it drains several square miles of Triassic rock in that vicinity. A regionally significant but less conspicuous divide runs approximately north-south along high ground just west of Gouglersville and separates Connestoga drainage from flow direct to the Schuylkill via Wyomissing Creek.

GEOLOGIC SETTING

The physical aspects of the land as well as the human uses of different parts of this area are profoundly influenced by their geologic foundation.

This section describes the general character of the geology in common language so as to be understandable to those without any background information.

The surface of this area is veneered with soil and other unconsolidated deposits which locally may be of appreciable thickness. Such deposits are sometimes treated as geologic units; but they have not been extensively considered in this report because a modern soil survey is available (Ackerman, 1970).

Red sandstones and conglomerates of Triassic age (about 190 million years old) are the youngest lithified sediments appearing in this area. They are intruded by part of the thick Morgantown diabase sheet and a few dikes of related composition. The sheet very locally, and the dikes more extensively, extend into older rocks beyond the limits of the basin in which the Triassic sediments were deposited. These intrusives are evidently slightly younger than the redbeds. The Triassic sediments were deposited across eroded ends of older rocks which had been folded by mountain building forces. Regionally, the depositional site was one of considerable relief, perhaps in the form of an intermountain basin. Not only locally, but regionally, a major portion of the basin fill was introduced by a large stream system entering the basin in and near the Sinking Spring area, and the Triassic rocks are atypically coarse and conglomeratic in this vicinity. Subsequent to deposition, the beds were regionally tilted northward with simultaneous development of warping or gentle folding about a northwestward axis. Considerable faulting accompanied the tilting in this area, though it is not entirely sufficient to explain the gentle folds. An abrupt decrease of the present basin width, accompanied by an increase in the tilting, occurs near the west margin of the area, but this is not evident in the quadrangle map, which does not cover the full basin width. A major transverse fault in the quadrangle is apparently related to this regional change in tilting and separates areas which differ somewhat in the character of deformation.

Older rocks have a much more complex history. Studies in regional sedimentology suggest that most of the rock units present in the Pennsylvania Appalachians formerly extended over this area, but the youngest which have not been eroded away are Ordovician shales about 450 million years old. Much of the erosion was apparently accomplished before the Triassic sediments were deposited, as the latter lie on rocks comparable in age to those presently exposed to the north. The lithology of the Triassic conglomerates, however, shows that somewhat younger rocks were the source. This indicates less erosion north of the basin than within it prior to the Triassic deposition, which in turn implies that the protobasin area was more elevated than the adjacent area during the erosional interval.

It is tentatively concluded on other evidence that the basin margin in the Sinking Spring area was initially defined by a reverse fault which raised the basin area. This faulting is a final effect of Paleozoic mountain building rather than directly related to the basin formation, but its presence is a strong influence in development of the Triassic structure.

The Lower Paleozoic rocks which remain exposed in the quadrangle represent several distinct periods of sedimentation. Initially, carbonates with basal sands nearly 600 million years old were deposited on a broad, shallow marine shelf which subsided more or less regularly for over 100 million years permitting the accumulation of many thousands of feet of sediment. A much more rapid rate of deposition followed and several thousand feet of shale and dirty sands accumulated; and locally, isolated slides occurred bringing exotic debris into the basin.

The later carbonates, represented by the Myerstown and Hershey Formations have characteristics indicating a change of depositional conditions toward one dominated by fine clastics. Elsewhere, these transitional formations were not deposited and some erosion occurred. A dolomitic conglomerate in the Hershey Formation represents debris from an eroded area. The rapid influx of clastic material represented by the shale defines the onset of mountain building processes (Taconic) which culminated in severe deformation of the rocks in this area.

This Lower Paleozoic interval of mountain building is known as the Taconic orogeny and includes several distinct phases. While the carbonates of the Great Valley were still accumulating, shales and coarser clastics were being deposited southeast of the carbonate bank. These older shales are the source of the exotic material in the later shales. The arrival of the exotic, or allochthonous, material apparently as a single complex unit, the Hamburg klippe, to its present neighborhood evidently preceded substantial deformation of the underlying rocks. In addition, however, the klippe itself evidently had a complex structural history prior to this deformation.

Subsequent to the emplacement of the Hamburg klippe, there was severe folding of the underlying rocks. No substantial interval is indicated, as it is evidently the northward advance of basement folding which provided the drive for the klippe. Folding of the Lower Paleozoic rocks and the basement was large scale and intense. The major structures produced were great recumbent folds which sheared off on their overturned limbs and carried detached cores of the basement gneisses northward. These great detached folds are known by the Alpine term, nappe. At least four or five of these great structures enter into the complex geological pattern of southeastern Pennsylvania. They appear to be about 50 to 75 miles long along strike and more than several miles wide. The three exposed along the northern edge of the belt of strong Taconic deformation between the Delaware and Susquehanna Rivers in each case show the more westerly nappe overriding the western end of its neighbor to the east. The overlap between the western Lebanon Valley nappe and the central Irish Mountain nappe includes the Sinking Spring quadrangle. These two nappes are derived from somewhat different parts of carbonate shelf and have distinctive sequences of strata which aid in their delimitation. These sedimentary sequences have been designated the Lebanon Valley and Lehigh Valley sequences respectively.

Associated with the development of the major nappes are folds, varying from a fraction of an inch to over a mile in wave length, and thrust faults within the nappe bodies, probably of a comparable range of magnitude. These second order structures are not identical in age, but reflect a partially decipherable sequence developed during progressive deformation.

Uplift accompanying emplacement of the nappes is shown by the detritus of its erosion and eventual reduction in the sediments of the Ridge and Valley province to the north, but there is no direct evidence of events in the Sinking Spring area for a period of nearly 200 million years subsequent to the Taconic deformation. Toward the end of the Paleozoic, the rocks of the Ridge and Valley province were folded in what has been called the Alleghanian orogeny. (The older term Appalachian orogeny was defined the same way but was extended to include deformation and metamorphism which was Taconic and possibly other ages.) Deformation of rock in the Sinking Spring area clearly younger than the main Taconic nappes shows evidence of movement consistent with the Alleghanian structures of the Ridge and Valley and undobtedly developed at the same time. The major feature of the Alleghanian in the Sinking Spring area is the development of two large thrust slices which brings portions of the upper limb of the Lebanon Valley nappe cutting across the junction of the lower limb of the Lebanon Valley nappe and the upper limb of the Irish Mountain nappe. Taconic folds were tightened and reoriented at this time, and some new folds may have been produced.

A minor compressional deformation younger than the late thrust sheets is deduced from minor structures, but it is probably still referable to the Alleghanian orogeny. Strike, however, is related to the trend of the Triassic basin, and it may be a significant factor in defining the Triassic grain. Possible up thrusting of the protobasin border at this time was previously suggested.

The history of the ancient gneisses of South Mountain and Grings Hill is even more complex. These gneisses were involved, though perhaps rather passively, in all the movements previously mentioned as having affected the Paleozoic rocks, and, in addition, hundreds of millions of years before that they had a more violent history. The story can be only dimly comprehended from the surviving evidence. The bulk of these rocks apparently were initially deposited as sediments perhaps not greatly different from the rocks of the present clastic belt. They were subsequently buried to great depth, and subjected to extreme pressures and elevated temperatures for one or possibly more extended intervals, with partial melting of the original sediments and possibly introduction of melted rock from greater depths. They were subsequently uplifted and eroded to a relatively even surface before the Lower Paleozoic rocks were deposited.

CONTRIBUTORS

Presentation of the investigations reported here as a quadrangle atlas was resolved when it became evident that a detailed examination of the structure and stratigraphy of the carbonate rocks might be regionally significant. At that time work on the Triassic and Precambrian rocks and the Hardyston Formation was complete or largely complete as part of larger studies of these units.

The late Dr. Dean B. McLaughlin of the University of Michigan conducted an extensive study of Triassic rocks in Pennsylvania. He mapped the area of the Newark Group in this quadrangle and submitted manuscript materials which provide the basis for the section on Triassic rocks in this report. This manuscript was prepared for publication by David B. MacLachlan with some revision to take into account the more recent studies of Glaeser (1966), and some expansion of the structural interpretation.

Dr. Tracy V. Buckwalter has made an extensive study of the Hardyston Formation and Precambrian rocks of southeast Pennsylvania. He has done the mapping and description of these rocks in this quadrangle. This map completes a series which includes the western end of the Reading Prong and all its outliers to the west.

David B. MacLachlan mapped the Martinsburg Formation and the Cambro-Ordovician carbonate area of this quadrangle, though he found that little had to be done to complete the work of Dr. Carlyle Gray on the Middle Ordovician Limestones. MacLachlan also undertook the incidental sections and general assembly of this report.

GEOLOGY OF THE PRECAMBRIAN ROCKS AND HARDYSTON FORMATION OF SOUTH MOUNTAIN AND GRINGS HILL

by T. V. Buckwalter

PRECAMBRIAN ROCKS

General Statement

The Precambrian rocks of the Sinking Spring quadrangle of South Mountain are identical to and continuous with most of those of the adjacent Womelsdorf quadrangle, and nearly identical to those of the Reading Hills in Berks and Lehigh Counties. They bear a considerable resemblance also to those of the highlands of northern New Jersey but are quite dissimilar to those of the Piedmont province, only 15 miles south. They consist chiefly of a group of older gneiss, mostly metasediments, which have probably been granitized to a greater or lesser degree. Because of the near identity to the Womelsdorf and Reading Hills rocks, some of the author's earlier published descriptions (1953, 1958, 1959, 1962) especially those of the Womelsdorf rocks, are used here, although most have been amplified or otherwise modified.

Granitic Gneiss

Distribution

Granitic gneiss and its varieties are by far the most abundant of the Precambrian rocks. They comprise about three-fourths of the exposed Precambrian rocks and have either replaced or invaded most of the remaining Precambrian rocks. Three small exposures of typical granitic gneiss crop out within about a half mile of the west edge of the quadrangle along Hospital Creek, and one more crops out near Cushion Peak. Granitic gneiss usually occurs as float like the other Precambrian formations. Locally, the float boulders are very large and abundant (Figure 4), indicating the bed rock is close to the surface.

Petrography

Typical granitic gneiss is light buff or bronze in color with an occasional pinkish cast. The grain size ranges from ½ to 3 millimeters, with most grains about 1 millimeter. The gneissic structure is poorly defined in most places and locally is absent. Where present, it is caused by an im-

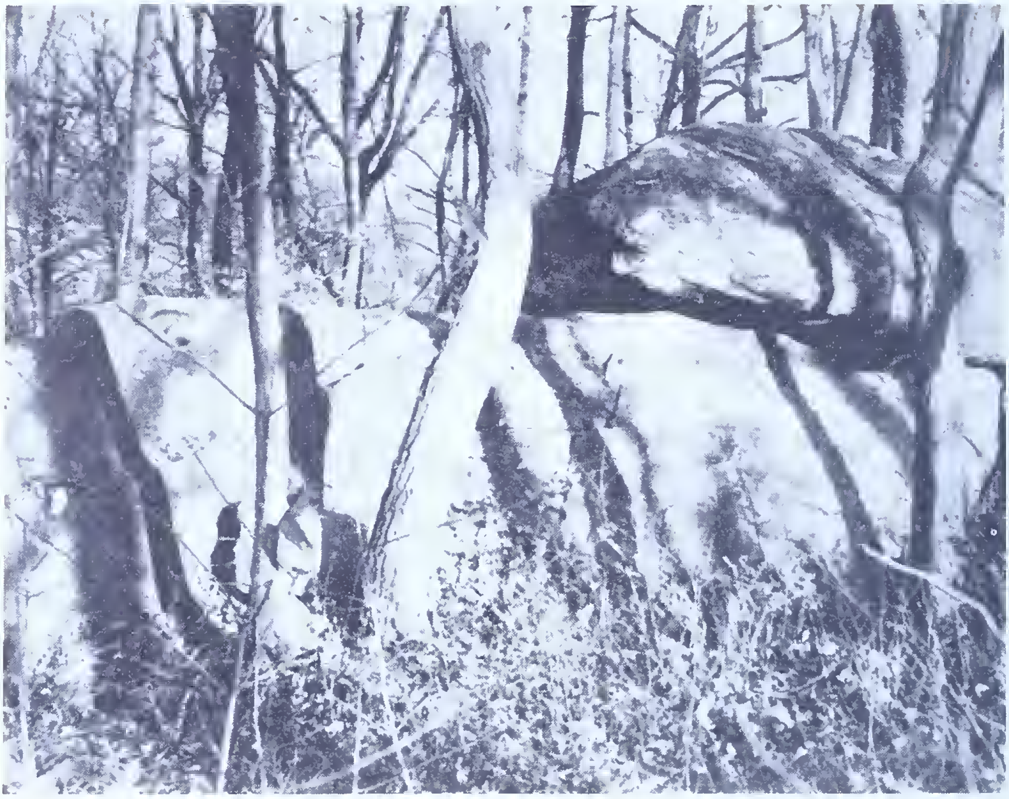

Figure 4. Large float boulders of coarse-grained granitic gneiss one-half mile west of Boulder Lake.

perfect parallel orientation of hornblende, chloritized hornblende, and, in some gneisses, slightly elongated quartz and feldspar grains. Several outcrops weather into slabs varying from 2 inches to 2 feet thick which break parallel to the weak gneissic structure. Weathering along conspicuous joints (Figure 5) in some places simulates this slabby structure. Locally, some granitic gneiss weathers into spheroidal boulders.

The mineral composition is somewhat variable; but everywhere, microcline, including microcline-perthite, composes about 30 to 50 percent and quartz 24-45 percent. Plagioclase varies rather uniformly from 0 to 20 percent. Orthoclase ranges from 0 to 20 percent averaging about 5 percent. The most common ferromagnesian mineral is hornblende which, except in migmatites, rarely exceeds 5 percent of the rocks. It is pleochroic from light yellow green to dark green. It is somewhat less abundant than the hornblende of the approximately equivalent "Byram gneiss" (Hague and others, 1956). In some areas where the ferromagnesian content is quite low, the rock is a leucogranite gneiss. A monoclinic pyroxene, probably augite, occurs infrequently, and green biotite is very rare. In one occurrence, a trace of hypersthene is present. The ferromagnesians are, in many places, altered to fine-grained aggregates of bright-green chlorite and locally to epidote. Accessories include apatite, magnetite, zircon and ilmenite.

Perthite occurs erratically. Nearly all is microcline perthite, locally composing 40 percent of the rock, but sparing to absent in places, especially in similar gneisses in the Reading quadrangle. It occurs almost entirely as string, bleb, or rod perthites, sometimes with a clear border to the host grain, suggesting exsolution rather than replacement. The plagioclase of the perthite has in places been sericitized whereas the host has been largely unaffected.

Plagioclase ranges from sodic oligoclase (An17) to sodic andesine (An31). In some localities, nearly all feldspar is sericitized and kaolinized but more commonly plagioclase is altered more intensely than potash feldspar. Most, but by no means all, of the plagioclase is twinned. Albite twins and some pericline twins are the only types observed. No Carlsbad twins or the rarer, more complex types like Manebach or Baveno twins were found.

According to Turner (1951) and Gorai (1951) a preponderance of albite and pericline twins, rather than Carlsbad or the more complex

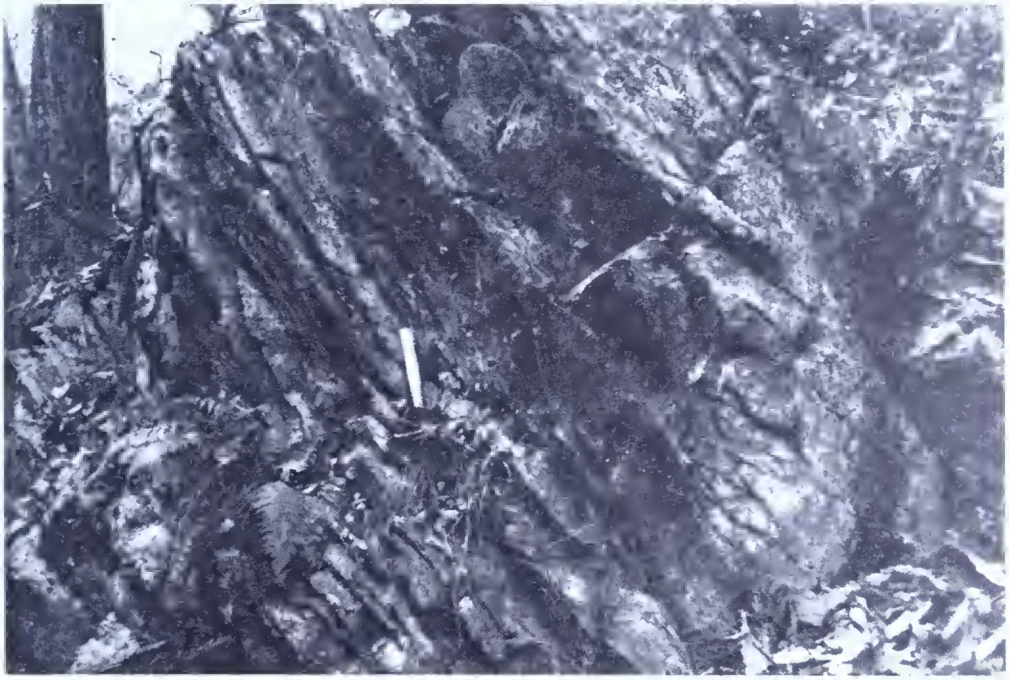

Figure 5. Slabby structure in granitic gneiss caused by weathering along prominent joints. Outcrop is located along Hospital Creek one mile southwest of Wernersville State Hospital.

twins, as well as the absence of twinning, suggest, that plagioclase and its twinning is of metamorphic origin. Despite the weak gneissic structure, most of the rock has been regionally metamorphosed. This is indicated by numerous sutured contacts, especially of quartz grains, microscopic crushed zones which have been partially recrystallized, mortar structures and by weak elongation of quartz and feldspar. Also the plagioclase composition of An17-31 indirectly suggests metamorphism to presumably the level of the almandite-amphibolite facies, for with rising grade of metamorphism, there is, according to Fyfe, Turner, and Verhoogen (1958, p. 218), a sudden jump from albite, An0-7, to oligoclase-andesine, An15-30, in quartzo-feldspathic schists and certain other rocks. Hornblende, and much less commonly, biotite, show some parallelism. However, some granitic gneiss shows nearly normal, interlocking, hypidiomorphic igneous texture.

A pinkish, pegmatitic variety of granitic gneiss occurs in thick float in a small area on the top of the hill a few hundred yards north of the old destroyed Galen Hall Hotel. The grain size varies from about 3 to 8 millimeters. Quartz comprises about 15 percent, microcline perthite 70 percent, sodic andesine (An34) 10 percent and ferromagnesians 5 percent. Some microcline perthite shows a closer-spaced "Scotch plaid" twinning than usual. Albite occurs in perthite as more or less parallel blebs; almost never as strings or rods as in the typical granitic gneiss. Under the microscope, plagioclase is invariably strongly clouded in plain light, mostly by sericite, and a little microcline perthite has also been sericitized. A few grains of myrmekite are present. The ferromagnesians consist largely of chloritized hornblende and a trace of epidote. The gneissic structure is due mostly to elongate quartz grains, some of which are five times as long as wide. Occasionally, thin xenolithic seams of unreplaced hornblende gneiss up to five inches long, lie largely parallel to the gneissic structure.

An unusual sheared variety of granitic gneiss occurs at several places along the north front of South Mountain within about a mile both east and west of Wernersville State Hospital, and also for several hundred feet along the west side of the Fritztown Road about half a mile northeast of Fritztown. Most of this variety exhibits a nearly schistose, foliate structure marked by parallelism of quartz and feldspar occuring in augen-like lenses and bands about 1 millimeter thick and in places up to 15 millimeters long. The ferromagnesian minerals have been strongly chloritized and drawn into thin bands parallel to the quartz and feldspar lenses. Much of the gneiss with little or no ferromagnesians somewhat resembles sheared arkose of the Hardyston Formation. All of the sheared gneisses occur on or near the major thrust (see section on structure).

Nearly half of the crystalline rocks consist of migmatites formed by partial assimilation or replacement of hornblende-pyroxene gneiss by granite and related pegmatites. Despite the large areal extent, only one outcrop was found, which is by the road on the west side of the Hospital Creek Valley, 1000 feet west of the State Hospital. However, float is locally abundant. All migmatitic gradations exist between typical granitic gneiss and hornblende-pyroxene gneiss. In a few places, hornblende-pyroxene gneiss occurs as sharply defined xenoliths in granitic gneiss; elsewhere it has nearly disappeared, occurring as vague diffuse patches of hornblende grains in the granitic gneiss matrix. In places the usual leucocratic gneiss has incorporated nearly 20 percent of its volume as hornblende from the assimilation or replacement of hornblende-pyroxene gneiss.

The most common of these migmatites is a medium gray granitic gneiss that is distinctly darker than typical granitic gneiss. Pink or light-brownish colors are much less common, unlike typical granitic gneiss. The grain size is one to two millimeters in most places, although in areas of pegmatite, it is one centimeter. The minerals composing it are almost the same as in ordinary granitic gneiss, but the proportions differ, mainly in that hornblende is much more abundant, ranging up to 18 percent. Oligoclase is more abundant in the darker varieties than in typical granitic gneiss. Orthoclase and orthoclase perthite, totaling about 25-40 percent, are much more abundant than in typical granitic gneiss in which microcline and microcline perthite predominate. Hypersthene is slightly more abundant, ranging up to 35 percent. Sodic andesine (An30) is more common in the darker varieties in which it is about 15 percent, than in most typical granitic gneiss. The gneissic structure is much more prominent than in typical granitic gneiss. It is caused by alternate discontinous bands and lenses of dark hornblende or hypersthene, separated by lighter bands of plagioclase, alkali feldspar and quartz. Many of the lenses are three to four inches long and about one-quarter inch apart, but the size and spacing are highly variable. Some lenses are ill-defined because of the chloritization of the ferromagnesian minerals and the occurrence of isolated hornblende grains found between the lenses. This gneiss, in many places, weathers slightly reddish and is found abundantly in float in large angular to slightly rounded boulders.

A somewhat different, garnet-bearing migmatite crops out on a hill about 4000 feet west of the old destroyed Galen Hall Hotel and about 2500 feet north of Laurel Ridge. It is sparingly found in float about a half mile west of the Womelsdorf quadrangle. This light- to medium-grayish-brown gneiss is somewhat pegmatitic and contains some grains one centimeter long, though most are one to six millimeters in length. It is composed of approximately 40 percent microcline and minor microcline perthite, 20 percent quartz, 15 percent calcic oligoclase (An28), 10 percent orthoclase, 10 percent garnet and minor amounts of biotite, chlorite and accessories. Garnet is usually anhedral and partially embayed by quartz which also occurs as inclusions. Gneissic structure is quite evident as in most migmatites. The lack of identifiable hornblende, the presence of garnet and biotite, and the proximity to a known area of graphitic gneiss all suggest this rock was formed by replacement or injection of a garnetiferous, graphitic gneiss rather than a hornblende gneiss.

Correlation

The correlation of crystalline rocks between geographically separate areas is at best uncertain, even when the areas are relatively close. Under favorable conditions, correlation of a crystalline rock formation can be approximated by several means; ages obtained by geochronological methods, similar field relations to other rocks, similarity of mineral composition and texture, geochemical affinity and continuity of exposures.

Age determinations were made in 1969 for two South Mountain rock types (Appendix B), both from the adjoining Womelsdorf quadrangle. Muscovite from the Walters Mine pegmatite on the southwest side of South Mountain indicated a K/Ar age of 804±9 million years and biotite from graphitic gneiss about a half mile east of the west central edge of the Sinking Spring quadrangle gave a K/Ar age of 742±7 million years. The stated error ranges represent only the probable precision of the analyses and do not presume to account for possible argon loss after the primary crystallization. The coarse muscovite of the Walters Mine pegmatite should have good argon retention, and in the absence of any evidence of recrystallization it seems probable that this date is a fairly reliable indication of the time of pegmatite cooling, though even in this case the emplacement age may be greater. The small biotite flakes in the gneiss sample may reasonably be suspected of more significant argon loss with an actual age correspondingly older than the radiometric age. It seems likely that the actual age of gneiss metamorphism is the same or possibly somewhat greater than the pegmatite. The pegmatite dike is genetically associated with the granitic gneiss and both are apparently about the same age. Field relations indicate that the graphitic gneiss is older than the granitic gneiss, but it is hardly remarkable that it should have been completely recrystallized, at least to the extent of potassium-argon re-equillibration, at the time of granite gneiss formation. These ages agree fairly well with the age of about 840 million years of numerous samples from the New York and New Jersey Highlands rocks (Long and Kulp, 1962, p. 976-984). A sample from the "Highlands Gneiss" near Wernersville indicated an age of 821±25 million years (Long and Kulp, 1962).

Between South Mountain and the Reading Hills of Berks county, correlation of granitic gneiss is almost certain despite a six-mile gap in outcrops, because the rocks are almost identical petrographically and the field relations with the other crystallines are the same. Farther east in Lehigh and Northampton Counties, the correlation is less certain, not only because of the increasing distance, but also because the granitic gneiss, here termed the Byram and described by Fraser (1941), includes a somewhat wider variety of rocks. According to A. A. Drake (personal communication) chemical analyses of granite gneiss from the Reading area (Buckwalter, 1962) are the same as the hornblende granite-alaskite suite mapped by Drake and co-workers in eastern Pennsylvania and northern New Jersey (Drake, 1967a, 1967b, 1969, 1970, Drake and others 1967) and is also identical with "hornblende granite gneiss" of Sims (1958) in the Dover, New Jersey area which the author has confirmed to be similar in petrography and field relationships. The hornblende content of the South Mountain granitic gneiss is rather low, but the large amounts of microcline or microcline perthite and moderate amounts of relatively sodic plagioclase are similar. The granitic gneiss has little resemblance to the quartz-sodic plagioclase gneisses of northern New Jersey such as the Losee gneiss (Hague and others, 1956), the albite-oligoclase gneiss of Ringwood (Hotz, 1953), nor is it it very much like the more narrowly defined "Byram Gneiss" described by Hague and others (1956) in the Franklin-Sterling area. In view of the distance from the New Jersey areas to South Mountain and the rather poor crystalline exposures of South Mountain and the western part of the Reading Hills, the suggested correlations are certainly tentative.

Origin

An origin characterized by replacement of hornblende-pyroxene gneiss by "granitizing" fluids has been previously described by the writer (1958) for similar rocks which are well exposed at Antietam Lake in the Reading quadrangle. The chief evidence cited there is the orientation of hornblende-pyroxene gneiss xenoliths in granitic gneiss similar to that of the hornblende-pyroxene gneiss country rock. No outcrops in South Mountain show this relation, but several large float boulders suggest similar relations (Figure 6). In some float boulders, the xenoliths are replaced to the point where they are now ghost-like streaks and patches of nearly assimilated hornblende-pyroxene gneiss.

On the whole, petrographic evidence in the South Mountain area is not very convincing for a granitized origin. However, Gorai (1951) has sug-

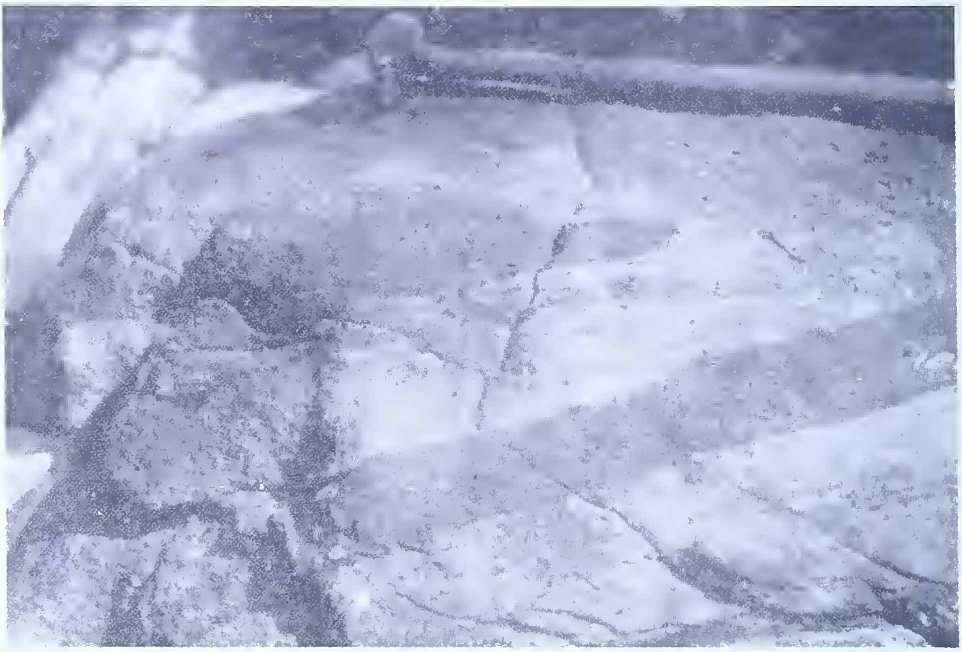

Figure 6. Xenoliths of hornblende-pyroxene gneiss in granitic gneiss on South Mountain in Womelsdorf quadrangle.

gested that metamorphic twinning in plagioclase may indicate a granitized origin for rocks like the granitic gneiss. His studies show that granitic gneiss rocks of igneous origin usually show Carlsbad twinning and occasionally the more complex twins, whereas granitic rocks of replacement or migmatitic origin usually show metamorphic twinning, namely albite and pericline types. Further petrographic evidences of replacement origin, mentioned by Moorhouse (1959, p. 278-279), and rather weak by themselves, but at least locally applicable here, are the presence of a more or less nondescript mosaic texture, a considerable variation in grain size within the area of a thin section, and irregularity in texture and composition. On the other hand, according to Drake (1969) the similar hornblende granite of the eastern Reading Prong has been mostly mobilized, though of complex metasomatic origin.

During the later stages or after granitization of hornblende-pyroxene gneiss, the granitic gneiss was subject to retrograde metamorphism as indicated by several textural features referred to earlier, such as: numerous sutured contacts, especially of quartz grains, microscopic crushed zones which have been partly recrystallized, mortar structure, weak elongation of quartz, and slight parallelism of hornblende and minor biotite. This metamorphism, superimposed on the newly granitized granitic gneiss, is apparently in the low greenschist facies, and chlorite, sericite and epidote, rather typical of low-grade metamorphic conditions, are widespread.

Hornblende-Pyroxene Gneiss

Hornblende-pyroxene gneiss is the second most abundant of the Precambrian formations, but occurs much more sparingly than granitic gneiss and only as float. A few small patches occur south of Wernersville, near the State Hospital, and in the southwestern part of the crystalline area of the quadrangle. Much of it has been so extensively replaced or assimilated by granite that it cannot be mapped separately. About half of the crystallines in this quadrangle consist of migmatites which have formed from the invasion and replacement of hornblende-pyroxene gneiss by granite.

Petrography

The rocks mapped as hornblende-pyroxene gneiss comprise a somewhat similar looking group of gneisses which range from a black, fairly well-foliated hornblende gneiss through hornblende-pyroxene gneiss and pyroxene-hornblende gneiss to a greenish-gray, weakly-foliated pyroxene gneiss. These rock are mineralogically similar, other than the relative quantities of hornblende and pyroxene, but differ somewhat in texture. Because of their close association in the rather small float areas, they have not been mapped separately. They are sometimes indistinguishable megascopically.

Pyroxene gneiss and pyroxene-hornblende gneiss are dark, greenish gray to nearly black rocks, which locally have a "salt and pepper" appearance resulting from contrasting black grains of ferromagnesian minerals among gray grains of plagioclase. Some of the greenish-gray color is due to chloritization and a little epidotization of the ferromagnesians. The grain size ranges from about 1 to 5 millimeters, and in a few rocks, ferromagnesians are distinctly larger than plagioclase. The mineral composition is about 50 to 70 percent labradorite (An60-63) and the remainder ferromagnesians, which include mostly clinopyroxenes (1-30 percent), hypersthene (19 percent), hornblende (trace to 18 percent) with pyroxene dominating in these rocks and hornblende in hornblende gneiss and hornblende-pyroxene gneiss. Orthopyroxene and clinopyroxene usually occur together, but one may be much more abundant than the other. Quartz is uncommon except in the migmatites in which the dark gneisses have been partly replaced by granitic material. The gneissic structure is weak in most pyroxene gneiss or pyroxene-hornblende gneiss and is absent in some instances. The gneissic structure which is present is caused by parallel orientation of elongated ferromagnesian minerals. No banding was observed.

Hornblende gneiss and hornblende-pyroxene gneiss are dark-gray to black with most grains about one to two millimeters in diameter. Hornblende is the chief mafic mineral, though the same pyroxenes occur as in pyroxene gneiss and pyroxene-hornblende gneiss. Occasionally, a little biotite is present and red garnet occurs in similar gneiss in the adjoining Womelsdorf quadrangle. The chief megascopic distinction between hornblende gneiss and pyroxene gneiss is the more common gneissic structure of hornblende gneiss. This structure is formed by imperfect parallelism of hornblende and sometimes pyroxene grains. These minerals are segregated in a few places into discontinuous, even bands separated by bands predominantly of plagioclase. All varieties exist between hornblende gneiss and pyroxene gneiss.

In both types of gneiss, hornblende usually exhibits pleochroism from pale yellow to dark brown. However, in one gneiss moderately invaded by granitic material, hornblende is light greenish brown to deep greenish brown. In another gneiss with little hornblende and abundant pyroxene, hornblende is pale green to medium green, simlar to the hornblende of granitic gneiss. The optic angle of the common brown hornblende is visually estimated at about 70° and the maximum observed extinction angle between the C axis and the slow ray is 23°. Biotite, which is rather uncommon, is usually pleochroic from pale yellow brown to deep brown. It occurs generally as elongate crystals somewhat embayed by quartz and feldspar. The ends of the crystals are frequently embayed and frayed. The clinopyroxene is largely pale-green augite with a maximum extinction angle, C axis to slow ray, of 54°. However, it closely resembles diopside, and the bulk of the elongate sections have extinction angles within the diopside range (34°-44°). A small amount of diallage, with very conspicuous parting, is locally present. The orthopyroxene is pale-pinkish hypersthene, frequently showing some color contrast to the greenish clinopyroxene. The pyroxenes are almost entirely anhedral, though a few are subhedral and elongated. They usually exhibit a mosaic texture with the other minerals. A few clinopyroxene grains are poikilitically enclosed within hornblende, and a very few crystals of clinopyroxene occur as cores within hornblende, suggesting hornblende is later than pyroxene. Most pyroxene is anhedral and shows no evident replacement relationships with either hornblende or the other minerals. The texture of both varieties is largely crystalloblastic, and very little of the original crystal shape is preserved in the rocks of the metamorphic facies now exhibited.

Field Relations

The field relations of hornblende-pyroxene gneiss with granitic gneiss are discussed mainly in the section on granitic gneiss and also in the section on quartz diorite gneiss.

In most localities where graphitic gneiss is abundant, hornblende gneiss occurs associated with it in the float. Separation of the two rock types along contacts is impossible because of the lack of outcrops. The exact structural relations are not clear in this area because the two formations have not yet been found together in an outcrop. However, at an outcrop only one half mile west of the southwest edge of this quadrangle, graphitic gneiss concordantly underlies a gneiss which is about intermediate in composition between hornblende gneiss and graphitic gneiss. True hornblende gneiss occurs in float in the immediate vicinity but does not crop out. A similar intermediate type of gneiss occurs in graphitic gneiss and hornblende gneiss float near the intersection of the Blainsport-Newmantown-Cocalico Roads, also the Womelsdorf quadrangle.

Origin

The hornblende gneiss variety appears to be, in part, of sedimentary origin. On South Mountain alone, the best evidence is the interbedding of graphitic gneiss, of nearly certain sedimentary origin, with gneisses intermediate in composition between hornblende gneiss and graphitic gneiss. In the nearby Reading Hills, the evidence is stronger because the hornblende gneiss is not only interbedded with, but also grades into, graphitic gneiss. Such interbedding may suggest metamorphosed sills or flows of perhaps diabase or basalt, but this appears unlikely in view of the gradational transition zone between hornblende gneiss and the metasediments. The intermediate gneisses may well represent sediments of composition between the carbonaceous sediments that resulted in graphitic gneiss and the impure calcareous sediments that resulted in hornblende gneiss. The minor quartz which is disseminated throughout hornblende gneiss at one locality may represent original quartz sand grains.

The origin of the pyroxene gneiss is considerably more uncertain than that of hornblende gneiss. In view of the gradation of pyroxene gneiss into the commoner hornblende gneiss and the fact that mineralogically they are similar, it is possible that pyroxene gneiss is also of sedimentary origin. The chief difference between them is the considerably weaker gneissic structure of the pyroxene gneiss. Field relations do not indicate very clearly either an igneous or sedimentary origin for the pyroxene gneiss and indeed this gneiss is poorly exposed only as float. Megascopically its lack of gneissic structure imparts a superficial igneous appearance, but microscopically the crystalloblastic and mosaic texture gives little indication of a former igneous origin. Few of the crystals are subhedral and little evidence is present for typical igneous textures such as porphyritic, diabasic or hypidiomorphic.

The mineralogy of both gneisses suggests that they have been regionally metamorphosed approximately to the sillimanite-almandite subfacies of the amphibolite facies. At approximately this facies, the color of hornblende changes from greens to browns (Miyashiro, 1961) as it is in most of these gneisses. Amphibolites very similar to these and at about the same stage of metamorphism have been described by Sims (1958, p. 25) in the Dover area of northern New Jersey and, for somewhat similar reasons, have been considered to be of questionable metasedimentary origin.

With some metamorphic rocks that have not undergone metasomatism, an estimate of the original source may be made from their bulk chemical composition. This is not feasible with hornblende gneiss because a variety of rocks with similar compositions but different origins may give rise ultimately to hornblende gneiss as a result of regional metamorphism. Thus, some tuffs, basalts, gabbros, and certain calcareous, iron-bearing sediments, like limy shales, all may give rise to hornblende gneiss. Occasionally the composition of a rock may be fairly well calculated by use of the optical properties of the constituent minerals. This method of determining bulk chemical composition is not very useful with hornblende gneiss because of the difficulty of correlating the optical properties of hornblende with its complex chemical composition. Friedman (1960, p. 73) has commented on the problems of this type of correlation including those of the amphiboles; and it has been jokingly noted by a well-known petrologist, who shall remain anonymous, that "Hornblende is the garbage can of petrology".

Graphitic Gneiss

Distribution

Graphitic gneiss and related rocks occur in several small areas of float in a discontinuous northeast trending belt which extends across the Precambrian area from near Laurel Ridge to within a half mile of Cushion Peak. No graphitic gneiss crops out, but two outcrops occur only 2000 feet to the west in the Womelsdorf quadrangle. Some of the petrographic description below is based upon these outcrops.

Petrography

Three related gneisses make up the bulk of the formation. The most common is a fine-grained, cream-colored or light- to medium-gray gneiss which, in a few places, shows a pinkish cast. Most of the grains are about one-half millimeter in diameter and only a few are as large as one millimeter. On weathering, the feldspars usually become dull white and the ferromagnesian minerals limonitic, so that the rock has a speckled brown and white appearance. The minerals include quartz, orthoclase, microcline, plagioclase (chiefly andesine), some graphite, biotite, pyroxene, and infrequently garnet. The relative amount of potash feldspar exceeds plagioclase, but in a few, potash feldspar is lacking. Hematite and apatite are accessories. The most common pyroxene is hypersthene, and augite is less abundant. The ferromagnesian minerals are chloritized in many places. Graphite occurs in flakes one to two millimeters in diameter, somewhat larger than the usual grain size of the rock, and disseminated throughout the gneiss. It rarely occurs in short, thin bands. Graphite occurs sparingly at many places. At only one locality, one of the two outcrops just west of the quadrangle, was the graphite content as high as an estimated 10 percent. The mineral here has a brilliant, glistening, tin-white, metallic luster which is a helpful aid in identification of this gneiss. The gneissic structure is more evident than in granitic gneiss, but it is less obvious than in hornblende gneiss. It results from parallelism of the ferromagnesians and graphite and a slight elongation of quartz and feldspar crystals.

Another abundant variety is a very light buff, coarser-grained migmatitic gneiss seemingly produced by injection of granite and related pegmatites into the graphitic gneiss. Granitic seams and veins parallel to the gneissic structure are abundant. Locally, pegmatitic injection and "soaking" have been so intense that little is left to megascopically indicate graphitic gneiss except a little graphite. On weathering, it shows the same speckled, blotchy brown and white appearance as the finer-grained variety. The grains range in size from one-half to six millimeters and the texture is irregular. The minerals are essentially the same as in the finer variety, except that the ferromagnesian minerals and graphite are less abundant, and potash feldspars are more abundant. The extra potash feldspar has apparently come from intrusion by the granitic and pegmatitic solutions which almost certainly formed at a higher temperature than the graphitic gneiss itself. The work of Tuttle and Bowen (1958) suggests that such solutions can form as low as about 600°C, which is probably at least 100° to 200° higher than the temperature of formation of graphitic gneiss which has been regional metamorphosed to the sillimanite-almandite subfacies of the amphibolite facies. The gneissic structure is much more evident than in the finer-grained variety and is the result of parallelism of ferromagnesians and graphite and a more pronounced elongation of quartz and feldspar grains. This migmatitic variety of graphitic gneiss, and to a lesser extent the finer-grained variety, closely resembles leucogranitic gneiss, especially because graphite is not always present. As injection and permeation by granitic "juices" increased, the resulting migmatite resembles more and more a pegmatitic granitic gneiss. The following criteria, published in an earlier report by the writer (1959) help to distinguish graphitic gneiss from granitic gneiss:

Graphitic gneiss	*Granitic gneiss*
1. Usually low in ferromagnesians except in biotite.	1. Usually some ferromagnesians, particularly hornblende and its alteration product, chlorite.
2. Usually strong elongation of quartz and feldspar crystals.	2. Generally weak quartz-feldspar elongation.
3. Some varieties are very fine grained (0.5 mm and less).	3. Usually medium to coarse grained (1 to 5 mm).
4. Usually weathers light buff to white.	4. Weathers buff to gray.
5. Fairly evident gneissic structure.	5. Usually weak gneissic structure.
6. Some float pieces weather fairly soft; broken without difficulty.	6. Mostly hard resistant float.
7. Tends to weather into small slab-like pieces.	7. Tends to weather into knobby, larger, rounded boulders.
8. Associated in places with gneiss intermediate in composition between hornblende-pyroxene gneiss and typical graphitic gneiss.	8. Frequently associated with hornblende-pyroxene gneiss.

A third, much less abundant variety is a fine-grained, medium- to dark-gray gneiss which in places shows a bluish to bluish-gray cast, slightly resembling some anorthosites of the Adirondacks. It occurs mainly at and near the outcrops in the graphitic gneiss area located north of Laurel Ridge. This gneiss contains chiefly plagioclase (andesine to labradorite), and pyroxene, predominantly hypersthene. Garnet, biotite, hornblende, and graphite occur in lesser amounts and rarely orthoclase and microcline are present. It is roughly intermediate in composition between hornblende-pyroxene gneiss and graphitic gneiss. Graphite is rare, and the darker phases of this rock may be easily confused with either hornblende-pyroxene gneiss, quartz diorite gneiss, or even the coarser phases of metadiabase. Locally, float pieces show a hard, buff, outer weathered zone about a half-inch thick and an inner blue-gray core.

Origin

Graphitic gneiss is very probably of metasedimentary origin and, in view of its present mineral composition, was apparently formed by regional metamorphism of a carbonaceous sandstone to approximately the sillimanite-almandite subfacies of the amphibolite facies. Graphite is usually considered an indicator of metamorphism of carbonaceous sediments (Heinrich, 1956, p. 223). The occurrence of biotite as the most abundant ferromagnesian mineral and the occasional presence of garnet also lends support to the sedimentary origin. Near Boyertown, in the Reading Hills, some quarry exposures and abundant float strongly suggest that graphitic gneiss, almost identical to that of South Mountain, is interbedded with marble, termed Franklin "limestone". As the marble is of certain metasedimentary origin, the interbedded graphitic gneiss would probably also then be metasedimentary. Quartz-graphite-feldspar gneisses of Lehigh and Northampton Counties (Fraser, 1941, p. 144-146), which are similar to the graphitic gneiss, are also intimately associated with marble. Microscopically, the graphitic gneiss shows no indication of former igneous textures. Finally, a graphitic gneiss from the Reading Hills, similar to those of South Mountain, contains two varieties of plagioclase, which is explicable only by a sedimentary origin.

Quartz Diorite Gneiss

Distribution and Name

This gneiss is least common of all the Precambrian rocks and occurs in only two areas large enough to be mapped; about a mile south of Wernersville State Hospital, the other about a half-mile southeast of the South Heidelberg Township School.

This rock was termed the Furnace Creek quartz diorite gneiss from a locality in the Womelsdorf quadrangle by the writer in an earlier paper (1953). The value of assigning formation names to certain crystalline rocks is rather doubtful, particularly because their origin, age, and correlation usually are not clear. As mentioned later, the quartz diorite gneiss appears to be a special sort of migmatite of rather variable composition rather than a bona-fide igneous rock, and hence it does not merit a formational name more than other migmatites of the Reading Hills areas. The current practice, in crystalline rock areas, is to assign specific lithologic names rather than formational names. These lithological names give a better indication of the mineral composition of the rock, which is one of the chief factors useful in correlation, and they also avoid a needless assemblage of formation names of uncertain value.

Petrography

Quartz diorite gneiss is generally a dark-greenish gray to dark-gray rock with a grain size ranging from one-half to three millimeters in diameter. It somewhat resembles the common anorthosites of the Adirondacks. As it grades into hornblende-pyroxene gneiss it becomes very dark gray to nearly black. It contains about 25 percent quartz, 50 percent andesine (An31-37), and the remainder is augite, hypersthene, hornblende, and biotite. In places, over 10 percent of potash feldspar is present, hence the rock should be termed granodiorite. Augite is usually fresh and relatively uncorroded, but hypersthene is largely altered to a mixed aggregate, in part sericitic. Sericite contains potassium, hydroxyl, and aluminum ions which are not found in hypersthene, hence some introduction of these ions is evident. The granitic material which helped form the quartz diorite gneiss was probably the agent which brought in these ions.

The gneissic structure is less well developed than in hornblende gneiss (Figure 7), but is usually more evident than in granitic gneiss or pyroxene gneiss. In some localities, the gneissic structure is the result of separation of bands of dark ferromagnesian minerals about one-sixteenth to one-eighth inch apart. The dark bands are usually not much over an inch long and not well defined though in a few places they are fairly conspicuous. The lighter bands contain greenish-gray quartz, plagioclase, and a little disseminated hornblende. In other places, the light bands are very short and ill-defined, and the gneissic structure is the result of a slight elongation of quartz and feldspar and parallelism of hornblende and biotite.

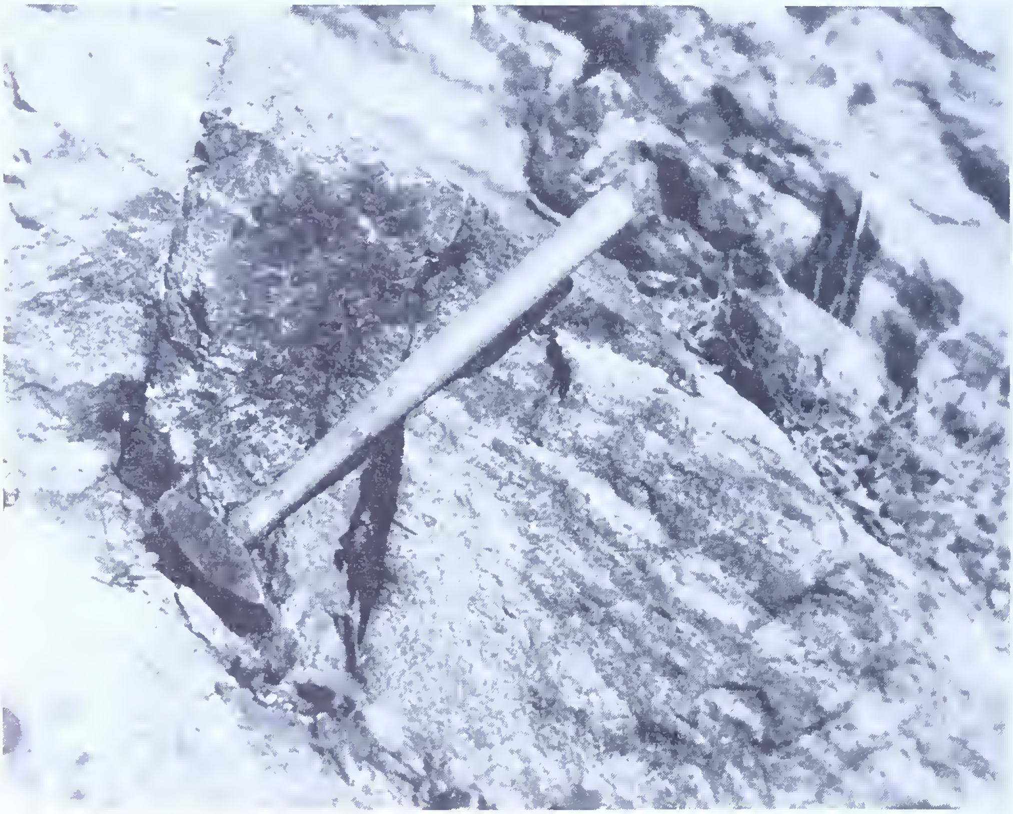

Figure 7. Weak gneissic structure of quartz diorite gneiss on South Mountain in Womelsdorf quadrangle.

Field Relations and Origin

The areas of quartz diorite gneiss, including unmapped very small occurrences, grade imperceptibly into either granite gneiss, hornblende-pyroxene gneiss, or into some of the common migmatites of the latter, which are formed by assimilation and replacement by granite gneiss. Rarely quartz diorite gneiss contains diffuse bands and clots of hornblende, but usually it is a homogeneous rock.

Quartz diorite falls mineralogically between granitic gneiss and hornblende-pyroxene gneiss, and appears to represent small, local masses of granitic magma that had completely or almost completely assimilated hornblende-pyroxene gneiss. The nearly homogeneous fluid magma then crystallized, but with a more basic composition. In a sense, the quartz diorite is only an unusual migmatitic variant of granitic gneiss, but its different mineralogy and field appearance justified mapping it separately. Somewhat similar processes are believed by Fraser (1941, p. 159-160) to have formed migmatitic gneisses in Lehigh County of composition intermediate between granite and diorite gneiss.

Pegmatite

Distribution and Structure

Pegmatite and a little aplite are widely distributed throughout the Precambrian rocks but occur in limited quantity. Most pegmatites occur as dikes apparently a few inches to a foot in width judging by the float occurrence. Although outcrops do not occur so that exact structural relations can be determined, pegmatites appear to cut all the Precambrian formations except metadiabase. Most of them are found in granitic gneiss, into which they grade. None have been worked commercially for muscovite as in the adjoining Womelsdorf quadrangle.

Petrography

All the pegmatites observed can be put in the "simple" class defined by Landes (1933). The color ranges from white to brown, depending on the quantity of weathered ferromagnesians. The grain size is variable as may be expected with pegmatites. It ranges from one millimeter in the aplites to several inches in the pegmatites. The common minerals are quartz, microcline, including perthite, sodic plagioclase, orthoclase, biotite, and muscovite. Microcline is ever-present, sodic plagioclase less abundant, and orthoclase relatively uncommon. Some pegmatites, particularly those occurring as thin lenses in the granite gneiss, show a distinct gneiss structure due to a pronounced elongation of quartz and feldspar grains. This structure appears to have been superimposed on the original, heterogeneous pegmatitic texture.

Metadiabase

Distribution

Several metadiabase dikes cut the Precambrian rocks of the western part of the quadrangle. All are indicated only by float. Some are only a few hundred feet long, but one just west of Cushion Peak near the YMCA Camp can be traced nearly a mile. The width of the dikes is indeterminate due to a lack of outcrop, but to judge by the width of abundant float, most are probably a few feet wide.

Petrography

Metadiabase is dark-greenish gray to almost black when fresh, and weathers medium gray to brown. It is tough and resistant to weathering and in places forms float boulders locally known as "ironstone" which ring when struck by a hammer. The grain size is about one-half to one millimeter. The typical diabasic texture, characterized by euhedral to subhedral plagioclase in a matrix of anhedral to subhedral pyroxene, is present almost everywhere. Under the microscope, augite composes about 25 to 40 percent, magnetite 5 to 10 percent, and labradorite or andesine 40 to 60 percent of the rock.

Augite is usually neutral to very pale brown, in one instance with a slight pinkish-brown cast. Weakly developed polysynthetic twins with (001) as the twin plane were noted in one diabase and a few grains show twins with (100) as the twin plane. It is usually partly altered to greenish chlorite and some epidote. Green hornblende locally replaces augite, mostly along the edges of the crystals. Biotite usually occurs as a few tiny, shred-like crystals. In one diabase it appears to replace hornblende, in another augite. It is altered in part to green chlorite. Orthopyroxene was not observed though some of the diabase is so thoroughly altered that the residual pyroxene is very difficult to identify. All the plagioclase ranges in composition between An41 and An56, except in one dike where it is An35. Plagioclase is usually considerably sericitized and is in many places altered to a confused saussuritic aggregate. Magnetite is frequently euhedral, but often also subhedral to anhedral. Infrequently it shows skeletal crystals. Ilmenite occurs sparingly. It is often indicated by leucoxene, which appears whitish in reflected light. It occurs infrequently as thin, band-like intergrowths in magnetite. A slight amount of hematite staining is occasionally present. Quartz, apatite, and pyrite are accessory minerals. Quartz occurs as minute anhedra and also in rare micrographic intergrowths with feldspar. Apatite frequently occurs as elongate, nearly euhedral crystals and pyrite as anhedral grains in some places associated with magnetite.

The dikes are considered to be Precambrian inasmuch as they cut no rocks younger than Precambrian. All are petrographically similar both to the Precambrian dikes and to a post-Hardyston, pre-Triassic dike which occurs in the Reading-Boyertown hill. (Buckwalter, 1956). However, as only one post-Hardyston, pre-Triassic dike is definitely known in that entire area, it is probable that most of the dikes of South Mountain are Precambrian. They are not Triassic as dikes of this age are much less altered than the older dikes. Plagioclase in Triassic dikes is usually relatively clear, in strong contrast to the saussuritic aggregates of the older dikes. Alteration of augite to chlorite and epidote is much less common in the Triassic dikes than in the older ones.

Hardyston Formation (Cambrian)

Distribution.

The Hardyston Formation forms a high rim around the eastern end of South Mountain, comprises most of Grings Hill and also occurs in a very small area on the west edge of the quadrangle immediately north of Laurel Ridge. Cushion Peak, a well-know landmark near Fritztown (Figure 8), is underlain by the Hardyston. Most of the gneiss hills rise above the Hardyston rim except near Cushion Peak.

Stratigraphy and Petrography

The structural complexity and rather small exposures of the Hardyston render determination of the sequence of beds within the formation difficult for this quadrangle alone, but comparison of the lithologic types with better-exposed sections in the Womelsdorf and Reading quadrangles facilitates the determination of the stratigraphic succession. In most of the Reading Hills and in much of the Womelsdorf quadrangle, approximately the lower 20 feet of the formation is a coarse, occasionally arkosic, quartz-pebble conglomerate which locally contains pebbles up to three centimeters in length. This coarse conglomerate, described in detail by the writer (1962, p. 24; 1963, p. 22), appears to be absent in the Sinking Spring quadrangle. However, as the contact of the Hardyston and underlying gneiss is nowhere exposed in an outcrop, the absence may be more apparent than real. It is probable that some of it is missing because of shearing near the major thrust (see structural sections).

A group of conglomerates occur both in float and outcrop which rather closely resemble the Hardyston "transition" beds described by the writer

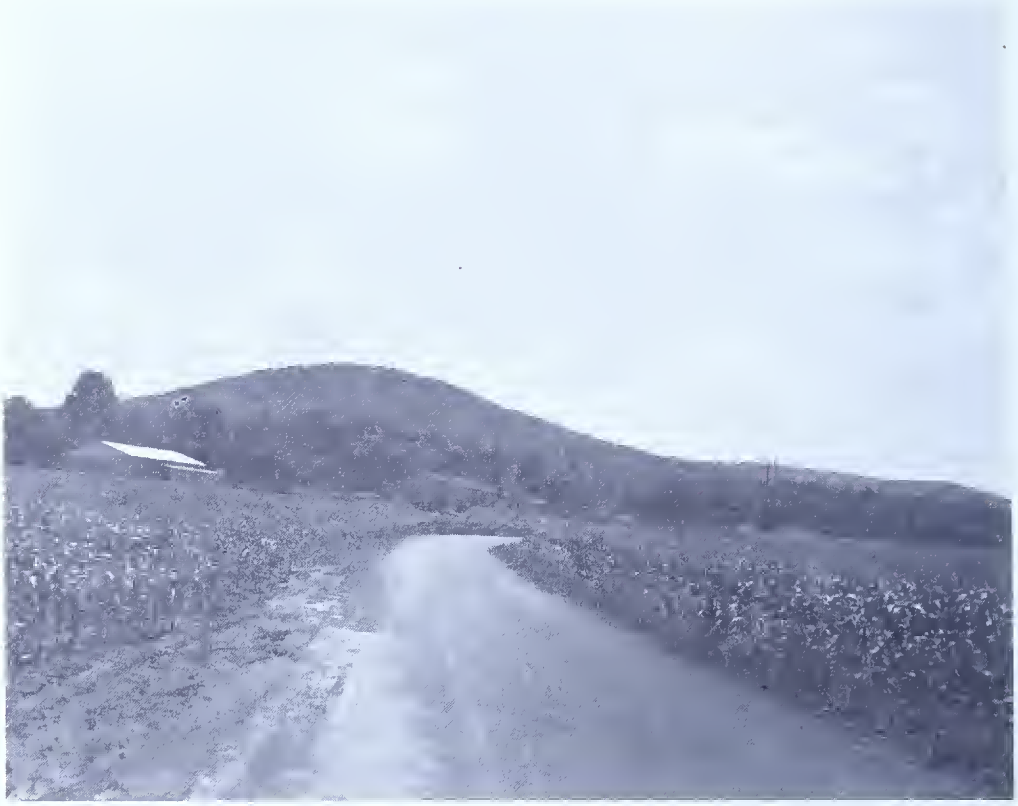

Figure 8. Cushion Peak, a well-known landmark near Fritztown, consisting of resistant Hardyston Formation of the Grings Hill thrust plate.

from exposures in the Reading quadrangle (1962, p. 26). The "transition" beds there overlie the basal conglomerate and differ from it by containing both smaller sizes and percentages of pebbles and granules. In the Sinking Spring quadrangle, "transition" beds crop out in two quarries on the north side of Grings Hill and occur as float on this ridge, on and near Cushion Peak (Figure 9), and very sparingly elsewhere. This conglomerate is white to light pink with about 25 to 30 percent framework of granules and pebbles ranging from 2 to 5 millimeters. Pebbles constitute 5 to 10 percent of the rock. Some granules and pebbles are pink. Quartz composes about 98 percent of the conglomerates examined microscopically. A little sericite and accessory magnetite and zircon form the remainder. Locally a few beds contain about 5 percent of weathered feldspar. Many of the granules and pebbles are especially elongated, the lengths not uncommonly five to ten times the width. Parallel crushed zones of tiny broken grains about .01 millimeter in diameter cutting through the larger grains as well as along the borders are common. Indeed, some conglomerates are semi-mylonites. Some of the grain boundaries show minute suturing. The grains appear to have been originally rounded, but deformation has destroyed much of the original shape. The beds are fairly massive, varying about one foot to six feet in thickness.

The beds above the "transition" conglomerates are a series of fine- to coarse-grained, quartzose sandstones and sedimentary quartzites frequently containing over 95 percent quartz. Fine-grained quartzose sandstones are most common, but many sandstones contain appreciable fractions of coarse grains and granules. Fresh surfaces are commonly white to very light gray, but blue-gray and greenish-gray were found. On weathering the color is usually light to medium gray, though a few surfaces are reddish or yellowish brown with iron oxide stains. Weathered bedding plane surfaces are occasionally slightly rough and irregular. In a few places

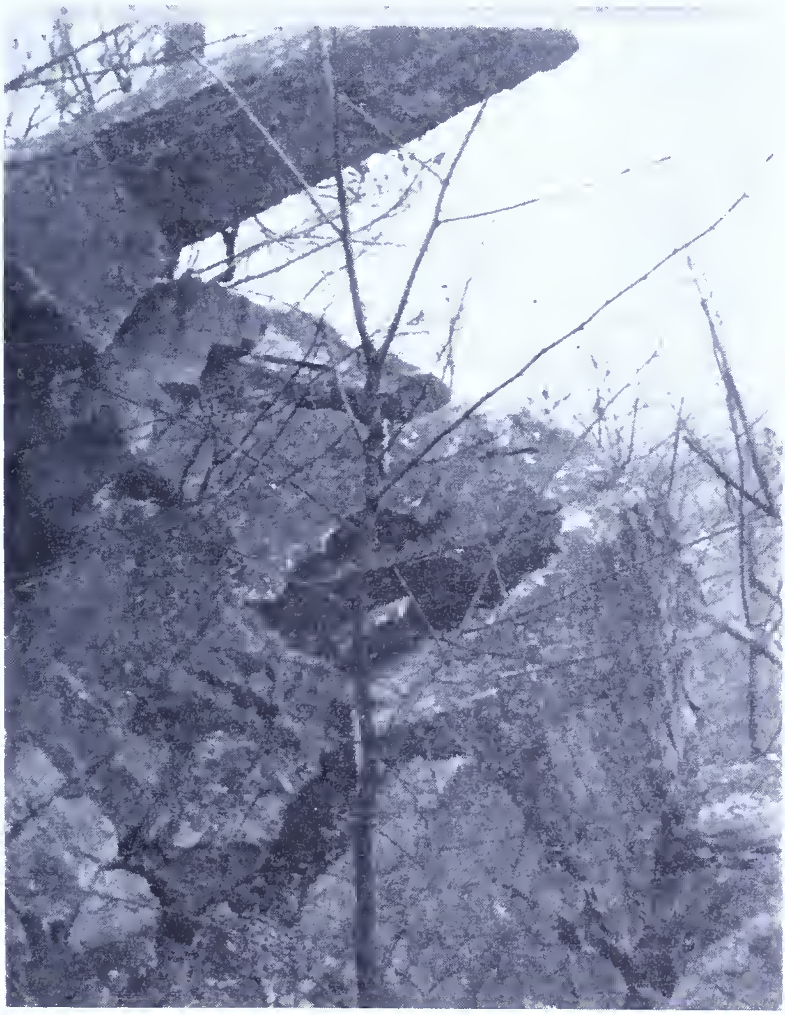

Figure 9. Gently dipping, thick-bedded Hardyston "transition" beds near top of Cushion Peak.

the sandstone readily weathers to loose sand. At one locality ill-defined cross-bedding occurs. The beds vary in thickness from one-half inch to six feet, but most are about six inches to one foot. Some of the sedimentary quartzite has a vitreous luster such that individual grains are hard to distinguish, but in others clay from weathered feldspars causes a slightly earthy appearance. Feldspathic sandstones containing about 5 percent feldspar occur locally as on the east end of Grings Hill. They seem to have little stratigraphic significance here or elsewhere in the Reading Hills (Buckwalter, 1963, p. 24; 1962, p. 26; 1959, p. 10). Potash feldspars, both orthoclase and microcline, are more abundant than plagioclase. Feldspar is almost indistinguishable from quartz in hand-specimen in some of the feldspathic sandstones except where weathered, though the difference is readily apparent in thin section. Under the microscope, granulation is quite common as in the "transitional" conglomerates; indeed in some feldspathic sandstones from Grings Hill, fully half the grains are granulated. Granulated streaks as well as grains of quartz greatly elongated parallel to the crushed zones impart, in places, a weakly schistose appearance to the rock. The appearance is enhanced by the local presence of a few percent of very fine-grained sericite. Some quartz grains also show minute sutured contacts. The granulation, elongation and suturing suggest that both cataclastic and mild regional metamorphism have deformed the quartzite. The quartzite was apparently only metamorphosed into the greenschist facies, because nearby, Martinsburg shale has been converted to sericitic phyllite and no profound textural changes occurred in the carbonate rocks immediately overlying the Hardyston. Magnetite, zircon and occasionally tourmaline are the heavy detrital minerals.

In much of the Reading Hills, especially near Allentown, jasper is found in the uppermost part of the Hardyston. While it was not observed in the adjacent Womelsdorf quadrangle to the west, a few float pieces occur in the Sinking Spring quadrangle about 2000 feet east-southeast of the South Heidelberg Township School and 100 to 200 feet south of the road which nearly encircles Cushion Peak. Megascopically it is a bright red to yellow-brown, partly cryptocrystalline rock, slightly banded in places, and containing a few vugs filled with tiny quartz crystals. Some of the float pieces grade into very-fine-grained limonitic or hematitic quartzose sandstone. Under the microscope this jasper is a combination of bands of clear, minute, partly spherulitic, chalcedonic aggregates, similar chalcedonic aggregates partly replaced by hematite, and very fine-grained quartz grains partly replaced by exceedingly fine-grained hematite. The jasper is apparently a replacement of Hardyston quartzite much as suggested by Fraser (1937, p. 57-61) for occurrences in Allentown quadrangle.

Whereas jasper elsewhere appears to be at or near the top of the Hardyston Formation, this float occurrence is only 100 to 200 feet north of Precambrian float, approximately where the basal conglomerate might be expected. However, this anomalous position perhaps may be explained by overturning of the Hardyston and thrusting of Precambrian rock, as is clear only one half-mile to the west along the mountain front near the township school and Wernersville State Hospital.

Thickness

The total thickness of the Hardyston Formation cannot be measured in any place in the quadrangle. Quarries on the north side of Grings Hill and the Grings quarry on the south side expose about 75 feet of Hardyston in rather uncertain stratigraphic positions. The writer (1963, p. 24) estimated the thickness at Eagle Mountain in the Womelsdorf quadrangle as 600 feet, at Mt. Penn in Reading quadrangle about 600 feet (1962, p. 27), at Lobachsville at the northeast end of Oley Valley about 400 feet (1959, p. 11), and 250 feet near Bechtelsville in the eastern part of the Boyertown quadrangle. Miller (1942) estimated it to be about 250 feet in Lehigh County and Drake (1967a) indicates about 100 feet in the Easton, Riegelsville and Bloomsburg (New Jersey) quadrangles along the Delaware. In view of the position of the Sinking Spring quadrangle between the Womelsdorf and Reading quadrangle, the thickness is presumably also about 600 feet.

STRUCTURE

Nine outcrops of Precambrian gneisses occur on South Mountain in this quadrangle on which the strike and dip of the foliation could be measured. Two of them near the State Hospital are close together, the others are widely scattered. Eight are in granitic gneiss or its migmatites and one in metasediments. The readings from the outcrops in these eight separate areas serve to give a general picture of the Precambrian structure but details are necessarily lacking. The gneissic structure trends from slightly northeast to approximately east-west, with dips south or east. The latter trend is in the northern and southern edges of the wider western part of the gneiss area and is somewhat like that of the gneiss of the Womelsdorf quadrangle to the west. To some extent, the shape of hornblende gneiss and graphitic gneiss areas fit this trend. However, as all of these areas were mapped almost entirely by float, and as they have been irregularly "soaked" and replaced by granite and pegmatite, precise conformity of their shape to the structural trends is probably not to be expected.

To some extent, the foliation of the metasediments parallels that of granite gneiss, but the outcrops do not give conclusive evidence. A similar structural picture has been noted in northern New Jersey (Sims, 1958; Hague, 1956) and the inference is drawn that granite was intruded as concordant sheets or phacoliths into metasediments. Buddington (1948) indicated a somewhat similar origin for granitic rocks of the northwest Adirondacks. An alternate explanation is that much of the granitic gneiss is "granitized" metasediments, but specific evidence is weak both in this quadrangle and in the adjoining Womelsdorf quadrangle, as indicated in the section of this report on granitic gneiss. Several float boulders at various localities show evidence of oriented xenoliths of hornblende gneiss in granitic gneiss, some being replaced to the extent of indicating little more than parallel, shadowy streaks. Better evidence of such structures favoring a granitization interpretation is found at Antietam Lake in the Reading Hills (Buckwalter, 1958).

The outstanding Paleozoic structural feature of South Mountain of both Womelsdorf and Sinking Spring quadrangles is the great nappe with a Precambrian core flanked in part by Paleozoic sediments and bordered on the south by down-faulted Triassic rocks. This major structure forms the westernmost part of the Reading Prong, the southern extension of the New England geomorphic province, which extends from western New England across southeastern New York and northern New Jersey into southeastern Pennsylvania. The nappe here is a great plate of crystalline rocks and Hardyston Formation thrust over the Cambro-Ordovician carbonates and Martinsburg shales of the Great Valley. In the Sinking Spring quadrangle the thrust plate is separated into two parts, the larger western part continuous with that of the Womelsdorf quadrangle and a smaller eastern part located south of the town of Sinking Springs. The eastern part of the thrust plate is here termed for convenience, the Grings Hill plate, after the local name for the hill which is the topographic expression of the plate, and the western part is termed the South Mountain plate. The two parts are separated by a gap of about 1500 feet near Olive Leaf Chapel where the Triassic border encroaches on the underlying rocks.

Field evidence of the thrust is abundant in several places. From Wernersville State Hospital west about one and one third miles into the Womelsdorf quadrangle, Precambrian rocks of South Mountain directly overlie carbonate rocks of the Great Valley (Figure 10). Both in this part of the thrust plate, and further east where the Hardyston Formation forms the edge of the thrust, the crystallines and Hardyston are extremely sheared, in places being nearly mylonitized. On both the east and west ends of Grings Hill plate the Hardyston Formation overlies Martinsburg

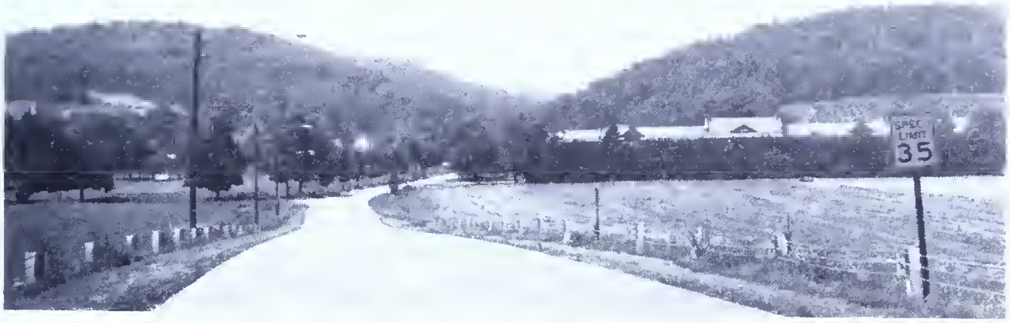

Figure 10. Precambrian gneiss of South Mountain (hills in background) thrust over Cambro-Ordovician carbonates of the Great Valley at Wernersville State Hospital.

shales in fault contact. Along a small part of the north central edge of this plate and the east edge near the Lancaster Pike, U. S. Route 222, granite gneiss overlies carbonate rocks. Also in the latter area, the main thrust plate appears to be thrust over a smaller one wherein the carbonates are thrust over the Martinsburg to the north.

Magnetic data obtained from aeromagnetic surveys in southeastern Pennsylvania (Bromery and Griscomb, 1967) also provide evidence for the existence of the thrust plate. The magnetic relief of South Mountain in the Sinking Spring quadrangle has a maximum of only about 400 gammas despite the fact that most of the mountain is made up of crystalline rocks which rise as much as 750 feet above the Great Valley. This is in marked contrast to about 1200 gammas relief on Mount Penn and other hills in the Reading Prong to the east, which are made up largely of crystalline rocks and which also have about the same topographic relief as South Mountain. If the crystallines of South Mountain continued at depth, the magnetic values should be much higher than they actually are. The crystallines are evidently underlain at relatively shallow depth by carbonates and shales of the Great Valley.

The Hardyston Formation is apparently overturned to the north along the entire north edge of the South Mountain plate, and deformed into narrow overturned folds along the north edge of the Grings Hill plate. Several outcrops in quarries and cuts indicate dips varying from 28 to 44 degrees south. The largest fold is the anticline in which the Hardyston wraps around the crystallines of South Mountain at Cushion Peak. It extends eastward to Olive Leaf Chapel and Fritztown as shown by float exposures. A core of granitic gneiss is exposed between these localities in one place in outcrop. Within this anticline are apparently smaller tight folds as indicated on section D-D′, Plate 1. These folds cannot be determined with exactness, due to scarcity of outcrops, but their presence is indicated by a much greater width of exposed Hardyston than would be expected from a steeply dipping formation only 600 feet thick. Also, the presence of Hardyston "transition" beds (p. 29), normally found near the Precambrian contact, a thousand feet east of the contact on Cushion Peak, strongly suggests a local anticline in this area. Some small tight folds of about 6 feet amplitude are exposed in slumped outcrops of thin-bedded Hardyston in a quarry along a road about one-half mile southeast of the old Galen Hall Hotel.

The Grings Hill plate comprises a large anticline overturned to the north, again with smaller nearly isoclinal folds which are partly exposed in Grings quarry on the south side of the hill (Figures 11 & 12 and section B-B′, Plate 1). The structure on the north side of the anticline is less clear, but apparently a small tight syncline occurs as shown in section

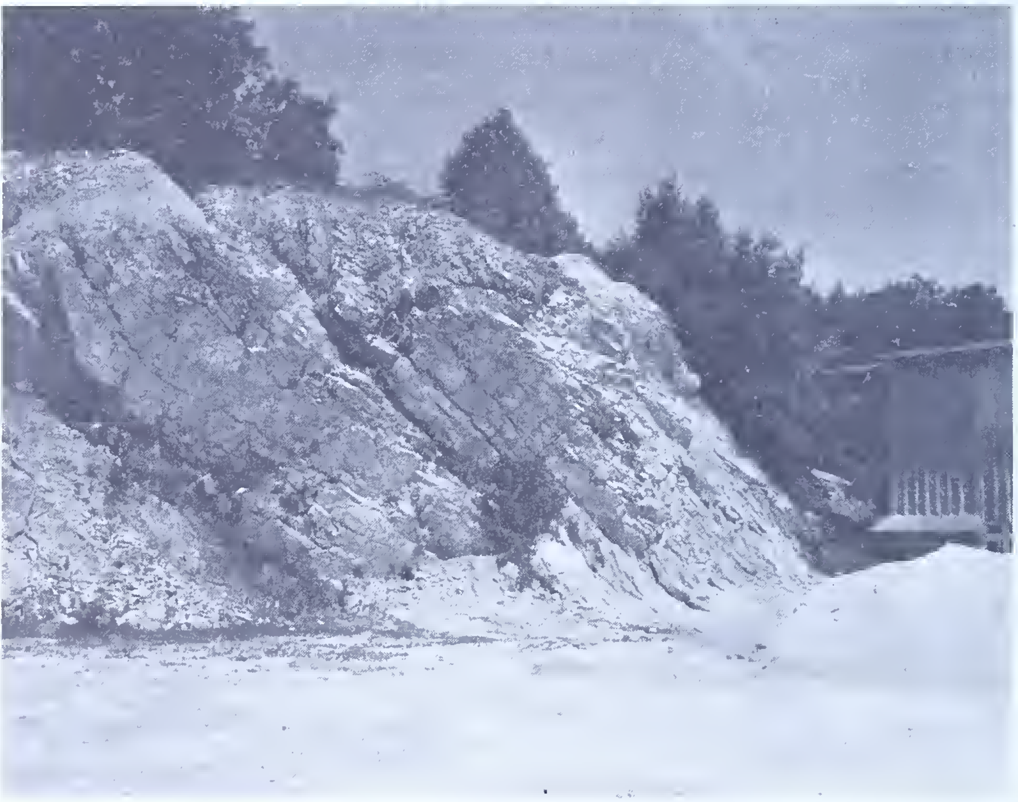

Figure 11. Isoclinal folds (right) in Hardyston Formation at Grings quarry, south side of Grings Hill, 1½ miles south of Sinking Spring Borough.

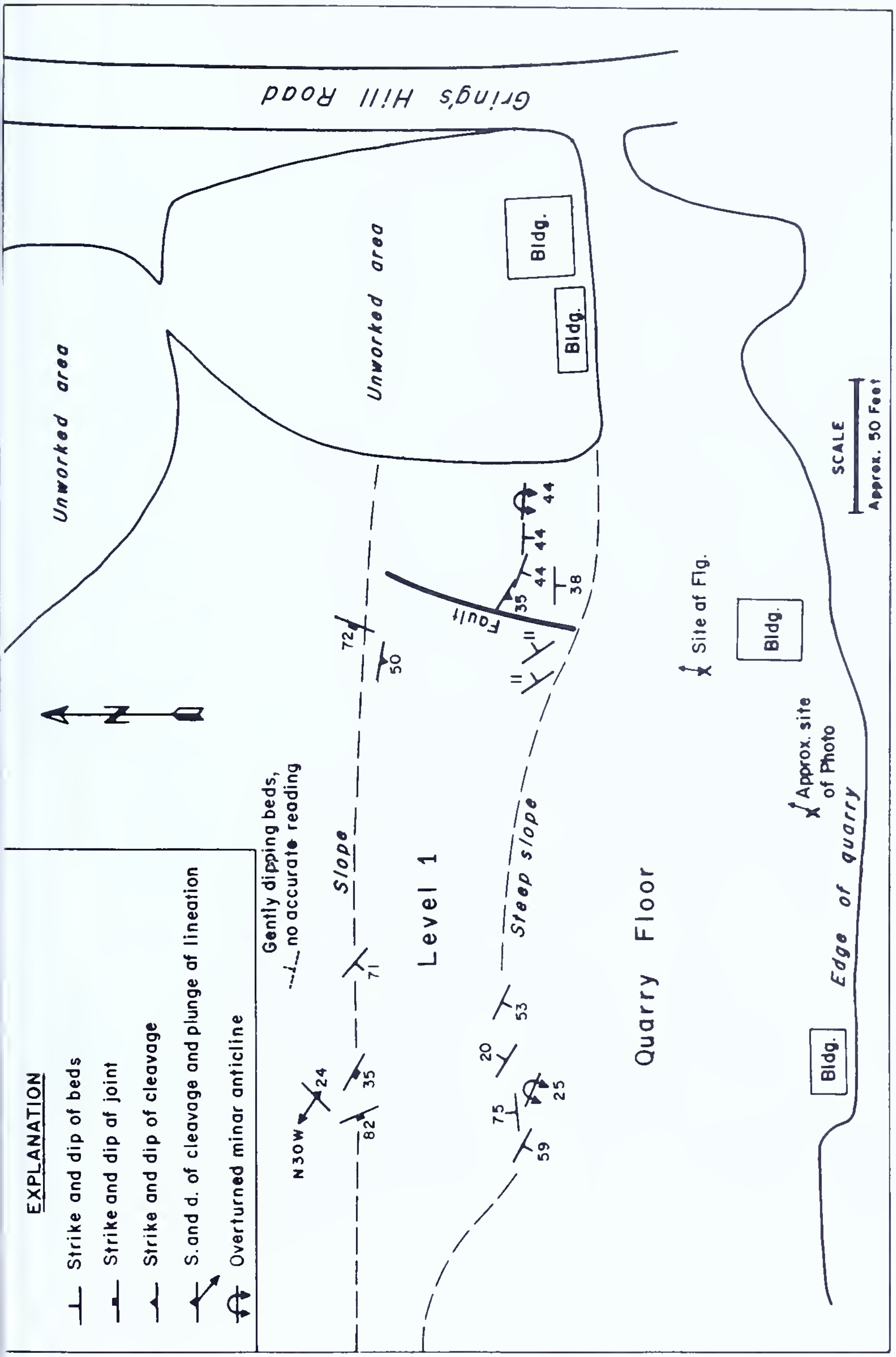

Figure 12. Sketch map of east end of Grings quarry.

B-B′, Plate 1. Its existence is inferred, as in the Cushion Peak area, from exposures of Hardyston too wide to be accounted for without folding. Slaty cleavage, approximately parallel to bedding, is present in one limb of the fold.

As indicated on the cross sections, the Precambrian rocks have participated in the folding. It is difficult to interpret the structure without at least some folding of the Precambrian. Even in the "thin skin" interpretations of deformation, like some by Drake (1967b) along the Delaware, folding of the crystallines is manifest. This is not surprising in view of the similarity mineralogically, and even texturally, of granitic gneiss, the commonest crystalline, and the lower, more feldspathic phases of the Hardyston. They are separated by no "weak" beds, which might permit a different mode of deformation for each, except the very local, thin, phyllitic "pinite" (Buckwalter, 1963), which infrequently occurs at the base of the Hardyston in the Reading quadrangle.

The interpretation of South Mountain and Grings Hill as a thrust plate, was originally made in 1935 by Stose and Jonas (p. 757-779). They considered it part of the controversial Reading overthrust which they believed extended from South Mountain to New Jersey. Earlier workers including Rogers (1858, p. 93-94, 103, 889) and d'Invilliers (1883, p. 36) believed the mountains of this area were overturned anticlines rising from the "synclinals" of the limestone valleys. Eaton (1912, p. 9-11) regarded South Mountain, specifically, as an anticline overturned to the north.

GEOLOGY OF THE GREAT VALLEY SECTION

By David B. MacLachlan

GENERAL REMARKS

It was noted in the "Geologic Setting" that this area contains rocks which variously have affinities to those exposed in the Lehigh Valley and in the Lebanon Valley. These subtly distinctive rock types have been elsewhere referred to as the Lehigh Valley sequence and the Lebanon Valley sequence (MacLachlan, 1967). The complete normal stratigraphic sections for these sequences are shown in the Correlation Chart (Figure 13). The base of the Lebanon Valley sequence is concealed by Triassic rocks, but equivalent rocks of the northern Conestoga Valley, south of the Triassic basin, are so comparable in mutually exposed portions as to give considerable weight to supposition that the concealed portion of the Lebanon Valley sequence proper must be quite similar to the lower part of the northern Conestoga Valley exposures. It is apparent from this figure that a somewhat different stratigraphic subdivision has been em-

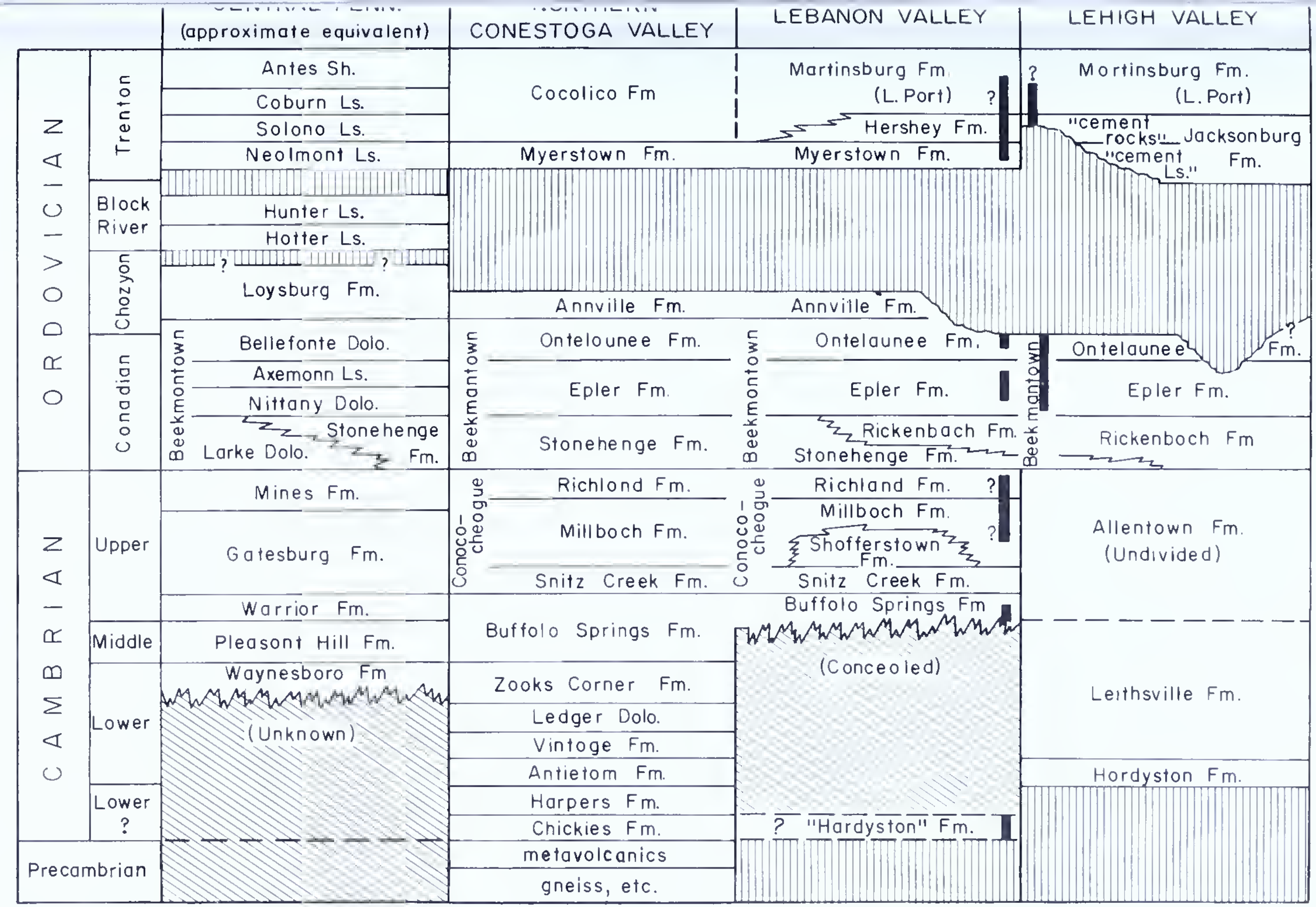

Figure 13. Correlation Chart of Cambrian and Ordovician units from Central Pennsylvania to the Lehigh Valley. Solid bars represent sections exposed in Sinking Spring quadrangle.

ployed in the two main sequences. The extent to which this reflects real lithic differences between the sequences will be briefly discussed in the section on stratigraphy. The significant point is that such differences do exist in close proximity in the Sinking Spring area, and they provide some indication of the very substantial low-angle thrusting and nappe development which dominates the complex structure of this area. The junction of the Lebanon and Lehigh Valley sequences represents an important stratigraphic discontinuity.

Detailed discussion of the structures of the area logically follows description of the stratigraphic units, but a few major elements should be named and located to render portions of the stratigraphic description intelligible, as the section is fragmentary owing to structural complications. The Grings Hill thrust lies near the topographic base of South Mountain and Grings Hill and brings the Hardyston Formation and Precambrian crystallines over Upper Cambrian rocks of the Lebanon (?) Valley sequence. The latter rocks form the upper plate of the Sinking Spring thrust which lies a variable distance to the north. The Sinking Spring thrust brings these Cambrian rocks discordantly over Ordovician rocks of both the Lebanon and Lehigh Valley sequences. The Lebanon and Lehigh Valley sequence terranes north of the Sinking Spring thrust are separated by the Hains Church fault, which is fundamentally the locus of a tear separating the Lebanon Valley and Irish Mountain nappes, but is marked by a high-angle fault of relatively small displacement. This is a profound structural and stratigraphic discontinuity reflecting a complete change in structural level and in structural style.

It should be noted that both sequences do show some degree of convergence in stratigraphic characteristics which is more or less pronounced at different stratigraphic levels. It is evident, except with respect to Middle Ordovician carbonates, that both represent portions of the same depositional basin which has been somewhat telescoped by thrusting with some intermediate deposits not exposed. If we were to accept the rate of facies change along the present strike of the exposure as indicative, the missing portion would represent a very substantial distance indeed. It is reasonable to suppose that the variation across strike is much more rapid, however. Nevertheless it would seem that relative dislocations of at least a few miles are required between the Irish Mountain and Lebanon Valley nappes to accommodate the contrasts in facies and thickness.

The structural evolution indicated in the Sinking Spring quadrangle involves syndepositional disturbance of the shales, better documented in the Bernville quadrangle to the north (Myers, 1969, and in preparation), followed by northward sliding of the shales down the advancing front of the nappe system on the Lorah thrust. Continuing advance of the nappes generated folds in the Lorah thrust and older rocks which were accompanied by thrusts which cut the Lorah thrust. Both the Lebanon Valley and Irish Mountain nappes were active during this major phase of nappe emplacement. Their movement was slightly convergent in the Sinking Spring area, and the lower limb of the Lebanon Valley nappe ultimately rode over the western end of the Irish Mountain nappe. Movement of the Grings Hill and Sinking Spring thrust plates was subsequent to this juxtaposition, though it could have originated in the late phases of Taconic movements in the nappe system. Associated structures suggest, however, that at least final movement of these plates is attributable to much later Alleghanian deformation which produced the general folding of the Valley and Ridge system.

STRATIGRAPHY

The approximate stratigraphic range of rocks exposed in the Sinking Spring area is shown by the heavy vertical bars on the Correlation Chart, Figure 13. Owing to the complex thrust dominated character of the area, few formations are entirely exposed and some are missing altogether. This incomplete exposure in the area where the two main stratigraphic sequences are observed in juxtaposition complicates evaluation of the extent of discontinuity between the sequences which are clearly distinctive in their typical exposures. This discussion is primarily concerned with the local exposures, but some effort will be made to place these rocks in their regional context.

Buffalo Springs Formation (Middle Cambrian)

The Buffalo Springs Formation was named from a Lebanon County locality by Gray and others (1958) where it was established as the lowest of five members of the Conococheague Formation. Geyer and others (1963) raised the Conococheague to group status and excluded the Buffalo Springs Formation in the opinion that the sands of the next higher Snitz Creek Formation are probably equivalent to the sands in the basal Conococheague Group in the Cumberland Valley type area. The Buffalo Springs Formation has also been recognized in the northern Conestoga Valley (Meisler and Becher, 1971) where it overlies a sequence of formations which presumably would also be present in the lower part of the Lebanon Valley sequence if it were exposed. These rocks are quite distinctly different from rocks of comparable age in the Lehigh Valley.

Owing to complex structure, only a small area at the eastern edge of the quadrangle is underlain by the Buffalo Springs Formation, and it is not known to be exposed. Sparse discontinuous exposure is encountered, however, a few hundred feet east of the boundary along U. S. Route 222. The rock is predominantly thin- to medium-bedded, light gray magnesian limestone with abundant phyllitic partings and weathers to platy debris (Figure 45). The rock seems fairly typical of the Buffalo Springs Formation in its type area, though perhaps a little more shaly.

Equivalent strata in the Lehigh Valley are evidently included in the Leithsville Formation of Wherry (1909) which was called Tomstown by Stose (Stose and Ljungstedt, 1932). The name Leithsville was revived (Howell, Roberts and Willard, 1950) and used for the Geologic Map of Pennsylvania (Gray, Shepps and others, 1961), though the name Tomstown was used for dolomite with shale partings (stratigraphically) below the Buffalo Springs Formation in the Womelsdorf quadrangle (Geyer and others, 1963). This dolomite, however, is best referred to as the Zooks Corner Formation. Throughout its known extent, which does not extend west of the City of Reading, the Leithsville Formation is poorly exposed. The upper part seems to be shaly, and in this respect it resembles the Buffalo Springs Formation, but it is apparently more dolomitic.

Probably no more than a few hundred feet of the Buffalo Springs Formation is represented in the quadrangle. The total thickness of the formation is about 1000 feet for a partial section in Lebanon County (Geyer and others, 1958) and may be as much as 3800 feet in the northern Conestoga Valley (Meisler and Becher, 1971). Inasmuch as this is evidently equivalent only to the upper portion of the Leithsville Formation which has a total thickness of about 1000 feet, this represents a major contrast between the Lebanon and Lehigh Valley sequences.

Conococheague Group (Upper Cambrian)

The name Conococheague Formation was originally applied to Upper Cambrian rocks of the Cumberland Valley in Franklin County, but it has been largely extended through the Great Valley for rocks of this age. It was raised to group status in the Lebanon Valley by Geyer and others (1963) who recognized four formations: Snitz Creek, Schaefferstown, Millbach and Richland in ascending order. Of these, the Schaefferstown seems to be a facies of the lower Millbach known only in Lebanon County. The others are also recognized in the northern Conestoga Valley (Meisler and Becher, 1971). Exposures in the type area are in the lower (overturned) limb of the Lebanon Valley nappe and are not continuous along strike with Conococheague Group rocks of the Sinking Spring quadrangle, which are evidently in the upper limb of the Lebanon Valley nappe and overlie the Sinking Spring thrust. The Sinking Spring rocks are thus derived from a somewhat more southerly position on the original carbonate shelf and are not identical with those of the Lebanon County type area. They perhaps more closely resemble the formations as described in the northern Conestoga Valley. Despite differences in detail, however, gross mapping criteria yield a subdivision which essentially is the same as the Lebanon County type area; and which is distinct from mappable subdivisions of equivalent strata in the Lehigh Valley.

The name Conococheague Formation has been applied to the Lehigh Valley occurrences (e.g. Stose and Ljungstedt, 1932) but the local name Allentown Formation (Wherry, 1909) has priority. There is no dobut that these units are largely correlative and sufficiently similar that this usage would be unobjectionable at the group level if the precise correlation were adequately determined, although the name Allentown Formation is well established in the eastern part of its exposure. In point of fact, however, the Buffalo Springs Formation, which underlies the Lebanon Valley Conococheague sequence, seems closely equivalent to the Elbrook Formation of the Cumberland Valley, which has an Upper Cambrian fauna in its upper part. Equivalent beds in the Lehigh Valley are included in the Allentown Formation which appears to be somewhat older at the base than rocks designated Conococheague Group or Formation elsewhere in Pennsylvania. For this reason it seems desirable to retain the name Allentown Formation in its original sense pending further stratigraphic study.

Howell, Roberts, and Willard (1950) attempted to divide the original Allentown Formation separating out the lower part as the Limeport Formation largely on faunal criteria. Drake (1965) reports that the proposed subdivision does not provide mappable units, and there is no indication that any potential lithic subdivision of the western Allentown Formation exposures corresponds to the proposed Allentown-"Limeport" contact.

The anticline at the eastern edge of the quadrangle evident in the map pattern of the Beekmantown Group at Cacoosing has the Allentown Formation exposed in its core less than 1 mile from the quadrangle boundary. This is the westernmost exposure of the Allentown Formation, which can be traced continuously along strike from this point eastward to the Lehigh County type area. The Allentown Formation certainly continues westward down the plunge of this fold; and it is an important element of the substructure of the Sinking Spring quadrangle, although it is nowhere exposed. The writer has established three mappable units in the Allentown Formation in the Reading area (work in progress), but it is not clear that this subdivision can be carried east of Berks County. While some parallels can be drawn with the formations of the Lebanon

Valley Conococheague Group, the mappable units of the Allentown Formation are neither identical nor apparently precise correlatives.

The Conococheague Group occurs in a band extending across the quadrangle on the south side of the carbonate valley where it composes the upper plate of the Sinking Spring thrust. The southern margin is delimited by the Grings Hill and Shillington thrusts. Exposure is particularly poor owing to substantial cover of quartzite and gneiss colluvium from South Mountain and Grings Hill; but, with supplementary data from the Reading quadrangle, the gross structure of this thrust slice can be established as a single major overturned anticline in which only partial sections of the Richland and Millbach formations are exposed.

Millbach Formation

The type section of the Millbach Formation is in eastern Lebanon County in the Womelsdorf quadrangle only a few miles from the Sinking Spring quadrangle. At the type section there may be more than 1400 feet of strata (Geyer and others, 1963) with light-gray, crystalline limestone with somewhat darker laminae in the lower part; light-gray to pink, interbedded crystalline limestone and dolomite with thin sandy beds and abundant stromatolites and intraformational conglomerates in the middle part; and light-gray, coarsely crystalline limestone interbedded with pinkish-gray, finely-crystalline limestone with fine shaly laminae, a few feet of rusty-weathering sandy limestone and abundant algal structures in the upper part. As compared to adjacent formations, the immediately conspicuous features are the light color and relatively large proportion of limestone.

The Millbach Formation of the Sinking Spring area lies in the upper, rather than the lower limb of the Lebanon Valley nappe and differs somewhat from the type section. It is so very poorly exposed, however, beneath the South Mountain colluvium that it is perhaps best characterized by comparison with the type area. Since the Sinking Spring belt occurs on the crest of an anticline with repetition of strata, probably only a few hundred feet of the upper part of the formation are represented in the mapped area. As compared with the type section, the Millbach here contains appreciably more dolomite and a significantly greater proportion of darker gray beds. Light-gray to nearly white beds are common, however, and provide a distinct contrast with the overlying Richland Formation which can be mapped with reasonable confidence from float fragments despite the heavy cover. While the light-colored limestones superficially appear unusually pure for carbonates of this area, they are abundantly silty and argillaceous, though they apparently contain less sand than the Richland Formation and relatively little chert has been observed. Beds of buff or yellowish, or more rarely dark-gray, phyllitic shale ranging from about an inch to a foot in thickness are not a major constituent of the unit but appear to be fairly common. The contact between the Richland and Millbach formations is not exposed in the Sinking Spring area, but it appears to be gradational in sections in the Reading area where it is best placed at the top of the highest very-light-gray limestone bed. The contact for mapping purposes in the Sinking Spring quadrangle is based on the occurrence of a significant proportion of light-colored limestone fragments in the float.

The best exposures of the Millbach Formation in the Sinking Spring quadrangle are found in abandoned quarries east of Montello Road and north of Reading Railroad, a scant mile southwest of the center of Sinking Spring Borough (Figure 14). A similar exposure, apparently somewhat lower in the section, lies just east of the quadrangle boundary about 1.6 mile southeast of Sinking Spring on Pa. Route 742. A few other small scattered outcrops are indicated by structural symbols on the geologic map, but exposure in general is very poor.

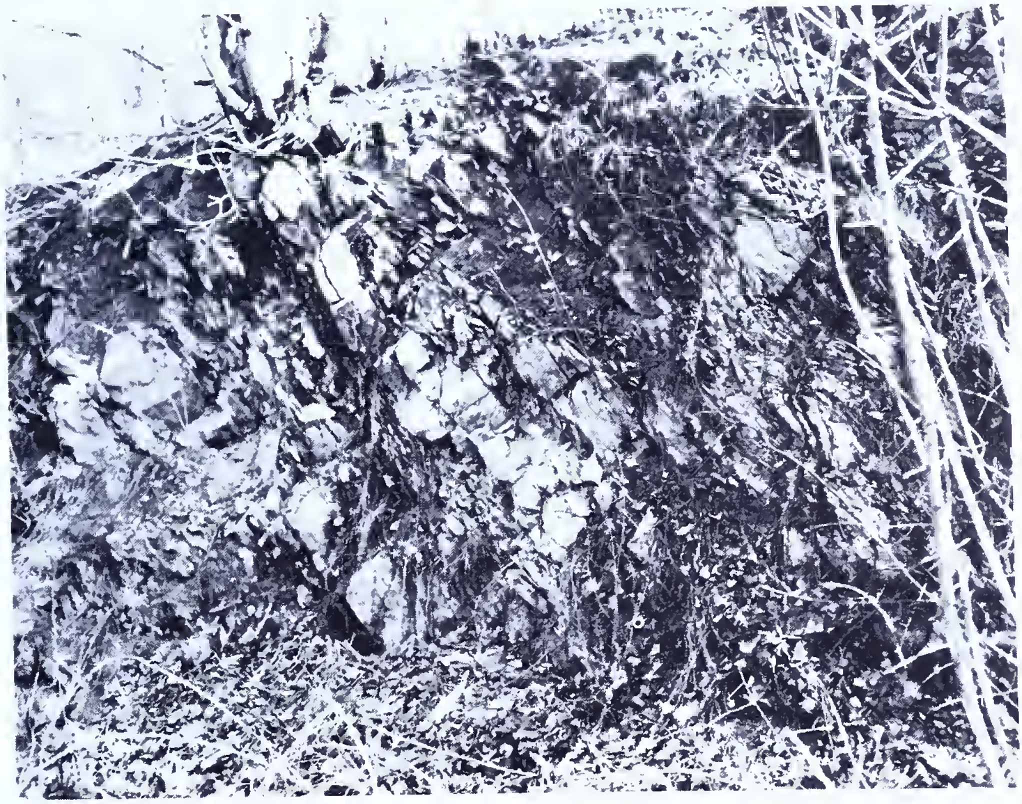

Figure 14. Millbach Formation, pinkish limestone and shaly beds. Railroad cut, Columbia Branch, at Montello.

An isolated patch of carbonate rocks occurs south of a Triassic instrusive mass east of Fritztown. This rock has been considerably metamorphosed and somewhat mineralized (magnetite-sulfides-chlorite-zeolites, etc.) and lies in the Wheatfield Iron Mines area which produced a few hundred thousand tons of magnetite iron ore in the 19th Century. Present exposure in this area is extremely poor, but isolated fragments lead to the tentative inference that carbonates belong to the Millbach Formation. Material observed by the author appeared to be quite silty, suggesting probably Cambrian rather than Ordovician age. It was predominantly calcareous rather than dolomitic and relatively light in color consistent with the suggested stratigraphic assignment.

Richland Formation

The Richland Formation of this area consists of thin- to heavy-bedded limestone and dolomite interbeds. The gross aspect of most outcrops is heavy bedded as the thicker beds clearly dominate in volume although not always in number. Subordinate terrigeneous clastic-rich laminae sometimes give a thin-bedded aspect to strongly weathered limestone beds.

In this area limestone appears to be somewhat more abundant than dolomite. It is commonly medium- to medium-dark gray, though colors may range from nearly white to grayish black. Except for the rare lightest varieties, the rocks tend to weather rather uniformly medium-light gray with variable amounts of buff- to dark-grayish-brown, terrigenous, clastic-rich laminae. The rocks are commonly quite silty throughout as well as having silt concentrations in the clastic-rich laminae. Sand is less abundant, but occurs both as scattered "floating" grains and occasional beds of calcareous (and dolomitic) sandstone about an inch to a foot thick. A concentration of sand near the base of the formation is not evident in the poor exposure with a sandy colluvial cover, but is evident in several well records. Stringers and nodules of dark-brownish-gray chert up to about 2 inches thick are fairly common in the limestones in some exposures. Lighter-colored chert has occasionally been recovered from soils overlying these rocks but has not been observed in outcrop. Well-developed algal cryptozoon structures are present but not abundant. Some of the more finely laminated limestones preserve features that suggest algal-mat origin and it seems probable that a large portion of the rocks in which their primary features are less perfectly preserved were also initially algal deposits.

The dolomites of this unit are generally uniformly medium- to medium-dark gray, very-fine to medium crystalline, and weather a uniform grayish yellow, buff, or brownish gray. They are often faintly marked with fine laminae on weathered surfaces or are entirely massive. These apparently represent supratidal, penecontemporaneous or primary dolomites on the whole. Less common varieties of dolomite include dolomitized oolite and cryptozoon beds. Dolomite also occurs as mottlings and partial replacements of limestone beds. In these occurrences it appears generally similar to and weathers like the massive dolomite beds. The dolomite is commonly as silty as the limestone beds, and occasionally sandy, but distinct terrigenous clastic-rich laminae are very rarely observed except in occasional examples in beds of clear replacement origin. Chert, such as found in limestone beds, is not known in the dolomite, but silica is often abundant as fine white vein quartz seams in fractures. The dolomite was apparently more brittle during deformation than the associated limestone and is commonly more intensely fractured. Where these fractures are not filled by vein quartz, these fractures commonly appear as crisscrossed indentations on weathered surfaces producing what has been called an "elephant hide" texture, which is a characteristic feature of most dolomites in this area at all stratigraphic levels.

Numerous exposures of the formation may be found scattered throughout the area on the north limb of the fold, but most are not very extensive. The best exposures are found near the west edge of the quadrangle in cuts along the Reading Railroad south of Big Spring (Locality 1 of Appendix, Figues 15 and 16) and in a roadcut on Fritztown Road about one-half mile southwest of its intersection with U.S. Route 422 in Sinking Spring (Locality 2 of Appendix). Less than 200 feet are exposed at the western locality and only about 65 feet along Fritztown Road. The two sections apparently do not overlap and give a fair representation of the character of the rocks included in this member.

With the exception noted below, there is no exposure of the Richland Formation in the southern limb of the fold in this quadrangle, but projection from the Reading quadrangle indicates the mapped distribution. Directly south of Wernersville less than 50 feet of heavy-bedded, buff to brown weathering, light- to medium-gray, calcareous to dolomitic sandstone which has been considerably silicified appears immediately adjacent to the Hardyston Formation in what is evidently a minor slice entrained in the Grings Hill thrust. The silicification probably is a consequence of the structural situation of these rocks without stratigraphic significance, but it contributes to giving these rocks an aspect which is not readily identified with the typical character of any of the Great Valley formations. There are a limited number of horizons, however, where this quantity of sand is encountered. Of the various possibilities, the closest structurally is the sandy zone at the base of the Richland Formation in the southern

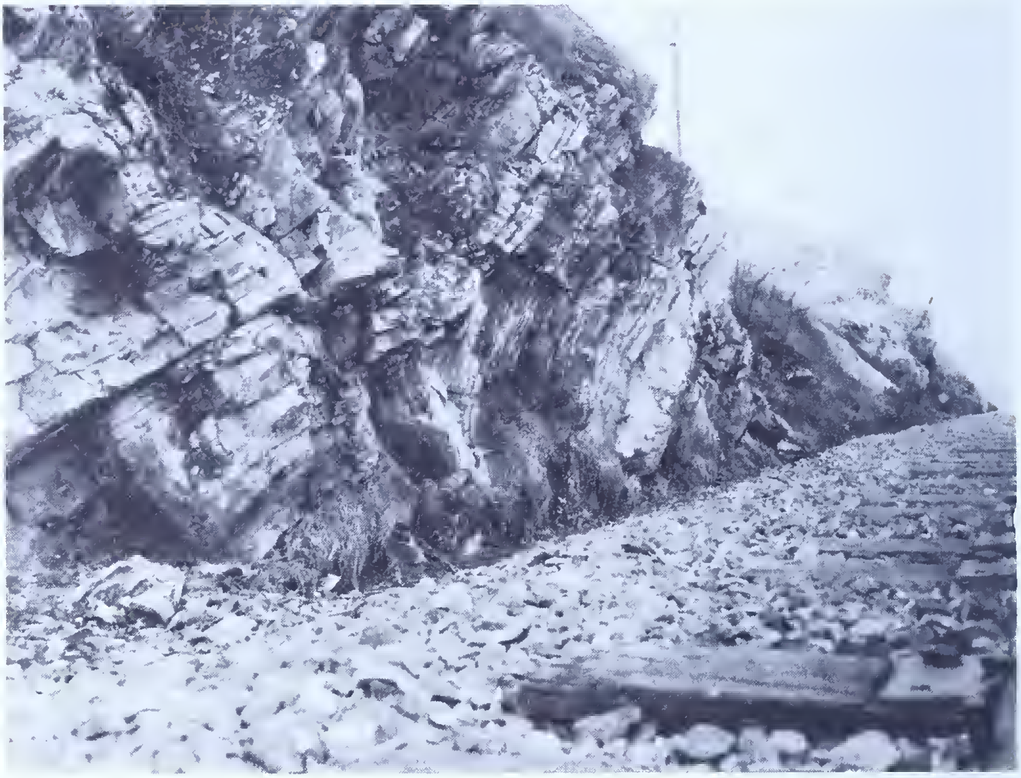

Figure 15. Exposure of Richland Formation, railway cut about 1 mile east of Robisonia.

limb of the Sinking Springs plate fold. This exposure is, therefore, tentatively assigned to the Richland Formation.

In comparison with the type section of the Richland Formation the rocks of the Sinking Spring quadrangle are less regularly cyclic and contain a substantially higher proportion of limestone than the well-exposed Upper Richland of Lebanon County. They may, however, be more like the less well-exposed middle and lower Richland of Lebanon County which is more calcareous than the upper part. This relationship is consistent with the conclusion that an indefinite portion of the upper Richland is absent along the Sinking Spring thrust. The Richland Formation of Sinking Spring, however, seems to be somewhat less pure than the most similar rocks in the type area with more shaly laminae and distributed terrigenous material. The sandy horizon near the base as recognized in well cuttings in this quadrangle apparently is represented by a sandy dolomite zone in the lower Richland Formation at the type section.

Beekmantown Group (Lower Ordovician)

The name Beekmantown has been used through much of the northern and central Appalachian area for carbonate rocks of Lower Ordovician (Canadian) age. The name was originally applied in northern New York State (Clarke and Schuchert, 1899) and introduced into Pennsylvania by Stose (1908); Ulrich (1911) apparently first applied this name to such rocks east of the Susquehanna River and thus to the Sinking Spring area. The name was originally applied and used in a formational sense, but it is now commonly treated as a group with regionally variable subdivisions.

The subdivision employed in the Sinking Spring area was developed by Hobson (1957, 1963) in central Berks County. It has been demonstrated to be useful throughout the Lehigh Valley (Drake, 1965) and in the Lebanon Valley as summarized by MacLachlan (1967). Hobson established a vertical succession of four formations in about 2300 feet

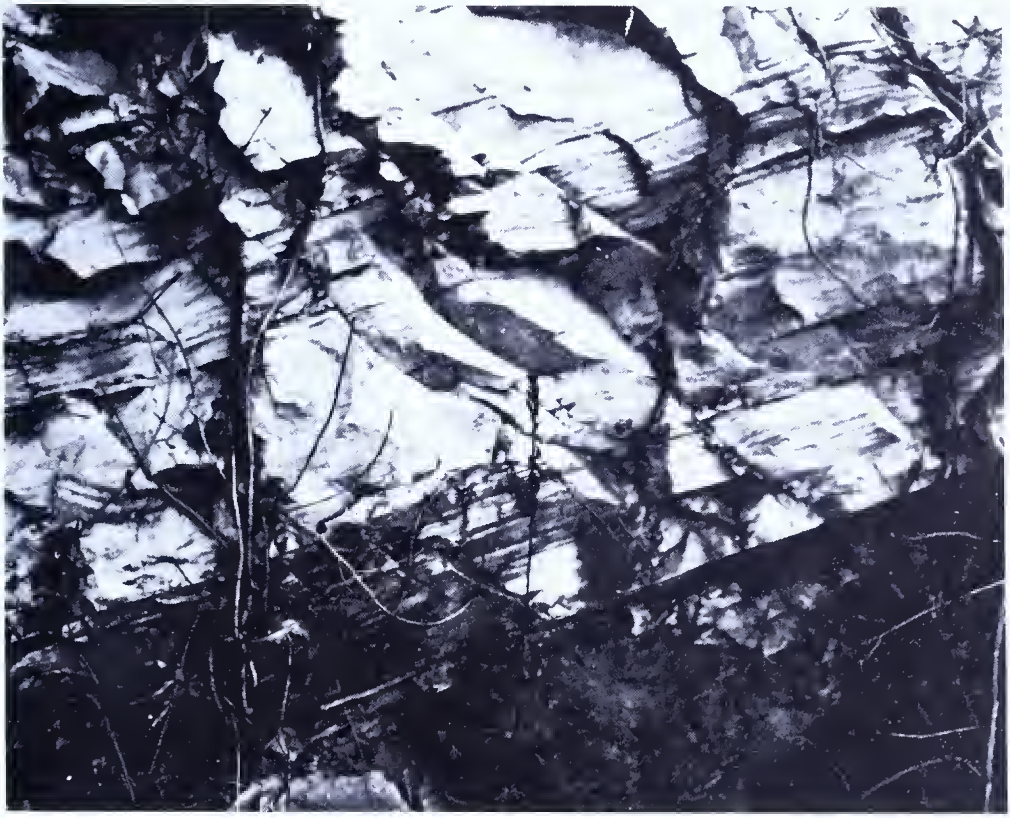

Figure 16. Detail of laminated limestone from Richland Formation just east (left) of Figure 15.

of strata which he recognized as belonging to the Beekmantown Group in the Reading area. These formations are fundamentally characterized by alternations between limestone and dolomite as the predominant lithology. Hobson's lowermost calcareous unit (Stonehenge Formation) and lower dolomitic unit (Rickenbach Formation) are laterally gradational as Hobson evidently recognized but did not explicitly discuss. The regional implications of this relationship were briefly examined by MacLachlan (1967). Both of these formations are presumably present in the substructure of the Sinking Spring quadrangle where their probable approximate position is shown on the cross-sections accompanying the geologic map (Plate 1), but they do not appear as surficial bedrock owing to the concealment of potential crop line by overriding thrust faults. The upper calcareous unit (Epler Formation) and uppermost dolomitic unit (Ontelaunee Formation) have been recognized throughout the areas of Lebanon and Lehigh Valley. These two formations do outcrop in the Sinking Spring quadrangle and are described in subsequent sections of this report.

On a regional basis, MacLachlan (1967) recognized the type area of Hobson's (1957, 1963) Beekmantown Group subdivision as lying in and toward the western end of the carbonate terrane characterized by the Lehigh Valley stratigraphic sequence. It was recognized that the same stratigraphic nomenclature was useful for mapping and in the descriptions of the Beekmantown Group in the Lebanon Valley. A complete section of the Beekmantown Group is represented by surface exposures in the Womelsdorf quadrangle (Geyer and others, 1963) which lies immediately west of the Sinking Spring quadrangle. The same formations as Hobson described may be mapped in this area and may be traced westward through the Lebanon Valley where they form part of the Lebanon Valley carbonate sequence (MacLachlan, 1967). Geyer estimates a thickness indefinitely in excess of 2650 feet for the Beekmantown Group in the Womelsdorf area. There are differences of relative thickness and lithology in the constituent formations between exposures in the Womelsdorf and Reading areas which are conspicuous relative to lateral variations along strike observed over comparable distances within the Lebanon or Lehigh Valley sequences. The present investigation shows that at least the exposed portions of the Beekmantown Group in both sequences extend into opposite sides of the Sinking Spring quadrangle without evidence of unusual lateral variability and abut with profound structural discordance across the Hains Church fault.

Within the Sinking Spring quadrangle, exposed limits of the Beekmantown Group are everywhere defined by tectonic contacts. In stratigraphic sections apparently free of tectonic interruptions, the base of the Beekmantown Group seems to be truly conformable on the underlying Cambrian in both the Lebanon Valley sequence and in the Lehigh Valley sequence west of the Delaware River vicinity. Through much of Pennsylvania, the rocks usually considered Beekmantown are conformable with or gradational to overlying rocks, and rocks so designated may include beds of Lower Chazyan (Lowermost Middle Ordovician age) (Neuman, 1951; Sando, 1956, 1957; Wagner, 1963, 1966; MacLachlan and Root, 1966; MacLachlan, 1967). MacLachlan concluded such a comformable relationship was characteristic of the Lebanon Valley sequence, though some previous workers (Prouty, 1951, 1959; Geyer and others, 1958; Gray and others, 1958) had followed the older interpretation of Ulrich (1911) that an obscure diastem existed between Middle and Lower Ordovician rocks. On the other hand, all investigators have concluded there is a substantial hiatus and some erosion between the Beekmantown Group and overlying rocks in the Lehigh Valley sequence. This relationship is considered more extensively in the section on Middle Ordovician unconformity, but the distinction between the two sequences is a conspicuous differentiating feature. Post-Beekmantown erosion in the Lehigh Valley sequence has probably removed some part of the original Beekmantown deposits throughout the Sinking Spring quadrangle east of the Hains Church fault.

Epler Formation

Hobson (1957) assigned interbedded limestones and dolomites with transitional contacts to the dominantly dolomitic strata above and below to the Epler Formation from exposures east of Epler School along the Schuylkill River, about 4 miles northeast of the Sinking Spring quadrangle. Essentially identical rocks appear in the anticlinal cores in the Sinking Spring quadrangle east of the Hains Church fault. Hobson (1963) fixes the thickness at the type section as about 800 feet. In the largest anticlinal core north of Sinking Spring Borough (Locality 3 of Appendix) he calculates a somewhat greater thickness as an extrapolation of a partial measured section but the structure revealed by the present mapping is not consistent with the basis of his projection. The north limb of the fold immediately east of the quadrangle boundary is continuous along strike with, and less than three miles from the type section. The width and apparent average dip of the crop suggest the Epler Formation at this point may be somewhat less (about 700 feet) but certainly does not exceed the thickness at the type section.

West of the Hains Church fault almost all exposed rocks of the Beekmantown Group belong to the Epler Formation. The structure is complex and beds are generally overturned. The two areas of exposure are discontinuous along strike owing to complications of thrusting, but they appear to belong to essentially the same major structural level. Exposed lithologies suggest that only the upper and middle parts of the formation are represented in comparison with a reference section for the Epler Formation of the Lebanon Valley sequence at Richland (Gray and others, 1958; Geyer and others, 1963). The width of the crop belt and the mean of dip values shown in the vicinity of Wernersville might indicate a thickness of more than a thousand feet of the Epler Formation, but known dip reversals associated with minor folds and a considerable possibility of repetition by thrusting suggest a considerably smaller figure. Geyer and others (1963) estimate that somewhat in excess of 650 feet of Epler are present in a probably more complete section in the Womelsdorf area, and it is unlikely that the thickness of the exposed Epler Formation in the western part of the Sinking Spring quadrangle will exceed this figure.

Rocks of the Epler Formation assigned to both the Lebanon and Lehigh Valley sequences have a generally similar aspect in this quadrangle but differ in detail. In fresh exposure it is heavy- to very-heavy bedded with conspicuous partings typically spaced about 1 to 4 feet. Limestone is conspicuously more abundant than dolomite. It is usually medium gray to occasionally medium-light gray, often finely crystalline though ranging from cryptogranular to medium crystalline, and is often faintly to distinctly laminated. The dolomites are almost always finely crystalline and perhaps a little darker gray on the average than the limestones. They rarely show any internal structure other than occasional chert nodules with the exception of a few calcite mottled beds. On weathering the limestones typically assume a medium-light-gray color which is commonly marked by grayish-yellow to buff, magnesian or silty laminae or less frequently mottled. In many cases the laminated character is so pronounced that weathered limestone exposures take on a thin-bedded or platy aspect. Dolomite assumes a grayish-yellow to buff color on weathering but retains its heavy-bedded aspect and commonly shows a faint suggestion of lamination by relief. While chemical analyses (Gray, 1951) and a few insoluble residue assays suggest an appreciable terrigenous constituent of both the limestone and dolomite, it is primarily argillaceous or very finely silty, and the relative scarcity of perceptibly abrasive quartz silt is a feature which most readily serves to distinguish the Epler Formation from rather similar appearing rocks in the Conococheague Group.

Considered separately, the exposed rocks of the Lehigh Valley sequence seem to be appreciably more dolomitic than those of the Lebanon Valley sequence; there are a number of limestones which are less prominently laminated, and lenses of fossiliferous fragmental limestone and oolite are more conspicuous. Fragmental limestone and calcarenite lenses are also reported from the Lebanon Valley sequence further west, though fossil material is rarely as well preserved as in the Lehigh Valley. These lenses are appreciably less abundant in the western sections than in eastern parts of the Sinking Spring quadrangle. While limestones of both sequences may assume a thin-bedded to platy aspect on weathering, this feature seems to be more persistently characteristic of the Lebanon Valley sequence exposures.

Owing to recrystallization of deformation, the depositional character of these rocks is not immediately apparent. It seems probable that they were quite similar to the partly correlative Rockdale Run Formation of the Cumberland Valley (Sando, 1956, 1957) and were composed of algal-mat deposits, detrital limestones largely formed of algal debris, and supratidal dolomites. On the basis of a higher proportion of dolomites and fragmental lenses suggesting relatively high mechanical energy, it would appear that the mean water depth averaged somewhat less in the area of Lehigh Valley sequence exposures than in the area of Lebanon Valley sequence exposures. Both, however, fall within the shallow carbonate bank environment.

The best exposures of the Epler Formation of the Lehigh Valley sequence are found near Cacoosing Creek and in the J. Brenneman Quarry. These exposures provide the basis for the section at Locality 3 of the Appendix. There are no comparably extensive exposures of the Lebanon Valley sequence Epler within the Sinking Spring quadrangle, though it may be observed in a number of abandoned quarries. One of the largest, most accessible, and least encumbered with trash fill is located on the east side of Wernersville, just south of the railroad (Figure 17).

Ontelaunee Formation

Predominantly dolomitic beds at the top of the Beekmantown Group were designated Ontelaunee Formation (Hobson, 1957) from type exposures in Ontelaunee Township along the Schuylkill River about seven miles northeast of comparable rocks in the Sinking Spring quadrangle. This formation has been recognized throughout the Lebanon and Lehigh Valley sequences. Hobson (1963) estimates that the typical thickness of the formation where fully developed in central Berks County is about 675 feet, but it is variably thinner to absent locally owing to subsequent erosion. From a composite section in Sinking Spring Borough and Cacoosing (Locality 3 of Appendix) Hobson calculates 504 feet in the Sinking Spring area, where the Ontelaunee Formation is tectonically succeeded by shales of the Hamburg sequence in a synclinal core.

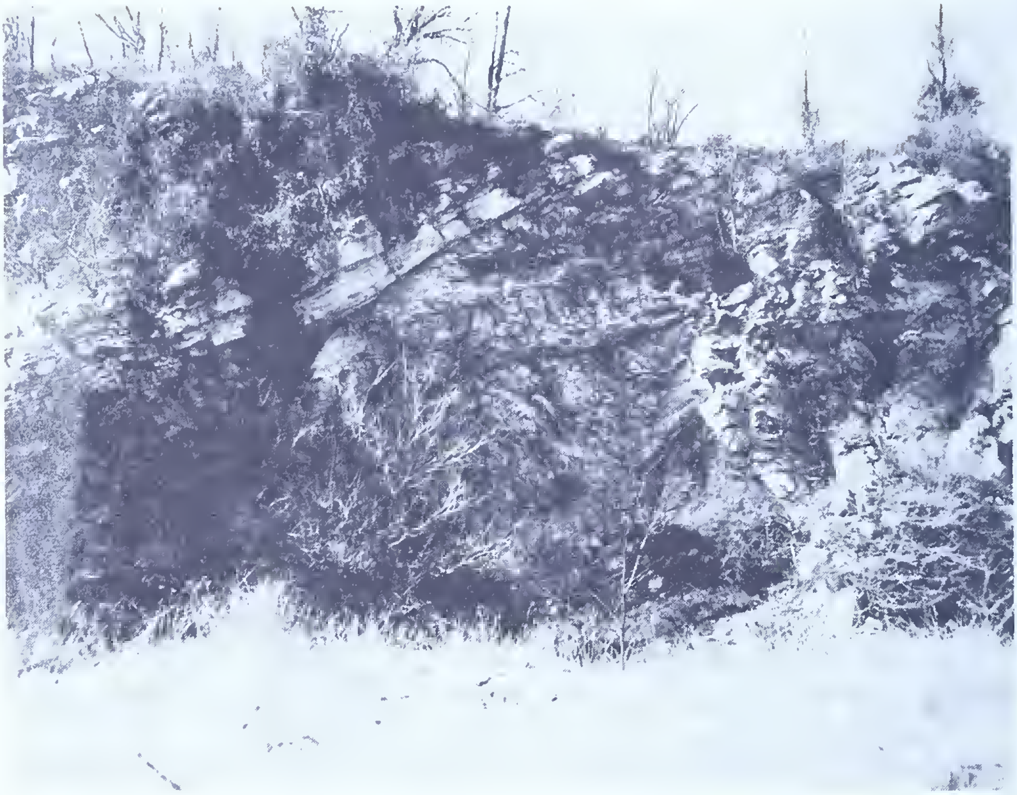

Figure 17. Epler Formation in quarry at east end of Wernersville. Note tectonic slicing within exposure.

Only a thin slice of the Ontelaunee Formation is present west of the Hains Church fault, extending about a mile westward from the fault into Wernersville Borough. Structural relations and lithologies indicate only an indeterminate part, approximately from the middle, of the formation is represented. Normal gradational contact of the Ontelaunee with the Epler Formation occurs in the Womelsdorf quadrangle immediately west of the Sinking Spring quadrangle boundary.

In the Lebanon Valley, original stratigraphic relations between the upper part of the Beekmantown Group and subsequent Middle Ordovician carbonates, cannot be established with confidence east of Womelsdorf Borough due to structural complications. West of Womelsdorf, fully developed sections of the Ontelaunee Formation are at least 100 feet thicker than any sections in central Berks County (Gray and others, 1958; Geyer and others, 1958; Hobson, 1963; MacLachlan, 1967). The rocks are mostly similar in both areas, but the additional thickness is largely accounted for by an uppermost member of pure, relatively dark dolomite which is nowhere present in the Lehigh Valley sequence and appears to be younger than any of the Lehigh Valley Beekmantown. The dark dolomite member is overlain with little or no unconformity by the Chazyan (lowest Middle Ordovician) Annville Formation of high-calcium limestone which has no equivalent in the Lehigh Valley sequence.

At and near the type section Hobson (1957, 1963) recognized three members in the Ontelaunee Formation. All are characterized by the predominance of medium- to medium-light gray, microcrystalline to finely crystalline, grayish-yellow to buff weathering dolomite. The upper member is distinguished by an appreciable proportion of medium-light gray, very fine-grained limestone interbeds. The lower member contains beds of dark-gray chert up to more than a foot thick. All of these members are apparently represented in the Sinking Spring quadrangle east of the Hains Church fault, but they are not consistently mappable under prevailing conditions of exposure. Rocks mapped as Ontelaunee in this area contain a higher proportion of limestone in the float and in some of the scattered outcrops than would be inferred from Hobson's descriptions, but float of the cherty member is sufficiently persistent to give reasonable confidence that the mapping of the stratigraphic unit is consistent with its definition.

The slice assigned to the Ontelaunee Formation west of the Hains Church fault and extended to the Lebanon Valley sequence is substantially less calcareous than much of the Ontelaunee immediately to the east and contains only rare nodules or stringers of dark-gray chert. The lithology is generally comparable to that described by Hobson (1963) for the middle member of the formation at the type section. The position of these rocks within the Lebanon Valley sequence has not been definitely established. Bedded chert appears near the base of the Ontelaunee Formation in most of the Lebanon Valley sequence and increases in prominence eastward; the absence of substantial chert near Wernersville suggests that the lowest part of the formation is not present. The dolomite is not that of the pure dark uppermost dolomite member of Lebanon County, so that the relatively low abundance of limestone interbeds suggests that the rocks represented are from the lower part of the formation.

Small exposures are sparsely scattered through the area mapped as Ontelaunee Formation east of the Hains Church fault, and there are a few small abandoned quarries, but no extensive continuous section is exposed. Readily accessible exposure of better than average quality is found south of U.S. Route 422 near the west edge of Sinking Spring Borough west of Cacoosing Creek.

The best exposure of the slice west of the Hains Church fault is to be found along and near the Reading Railroad just east of the Wernersville Borough line.

Middle Ordovician Unconformity

All investigators concur that there is a substantial unconformity above the Beekmantown in the Lehigh Valley. Where normal stratigraphic contacts are observed, the Beekmantown is commonly overlain by the Jacksonburg Formation of Lower Trenton Age, which regionally thickens eastward by addition of progressively older strata at the base. As previously noted, strata equivalent to the uppermost Ontelaunee Formation of the Lebanon Valley are not present in the Lehigh Valley and there is clear evidence locally of erosion of the Beekmantown beneath the Jacksonburg Formation. In much of the Sinking Spring quadrangle and the Reading area the Jacksonburg Formation is entirely absent. Gray (1952) observed that where the Jacksonburg Formation was present in Berks County, the normal contact with the Martinsburg Formation was gradational and the lower Martinsburg shales were calcareous; whereas, when the "Martinsburg" lay "unconformably" on the Beekmantown, the calcareous shales were absent and there was evidence of erosion of the Beekmantown. He concluded that the absence of calcareous shale and Jacksonburg, and at least some part of the Beekmantown erosion were the result of an erosional phase within Lower (?) Martinsburg time. However, in every case the writer has examined, terrigeneous clastics directly on the Beekmantown Group evidently belong to the Hamburg sequence and are in tectonic contact. It may be supposed, in this case, that missing portions of the Beekmantown Group have been sheared off; an inference quite consistent with slices of Beekmantown lying within the shale terrane near but not in the Sinking Spring quadrangle. While this relatively simple interpretation may be correct, the absence of any known Jacksonburg Formation associated with the Beekmantown slices and the relatively large volume of the Beekmantown apparently removed compared to that preserved in exposed slices argues for caution. Present interpretation of the clastic rocks eliminates the evidence for a supposed intra-Trenton unconformity, but the development at this level may well be more complex than has, or perhaps, can be reconstructed.

Westward overlap of the Jacksonburg Formation is an essential feature identifying the "Reading axis", an early warping axis inferred by Prouty (1959). The identification of a structural discontinuity on the west side of the area in which Lower Trenton rocks are absent leaves the paleogeography of the supposed "axis" in doubt, but there is no doubt of some relative pre-Trenton uplift of the west end of the area accumulating rocks of the Lehigh Valley sequence.

In the Lebanon Valley west of Womelsdorf, where structural conditions permit the establishment of a normal stratigraphic sequence for the upper Beekmantown Group and Middle Ordovician carbonates, Middle Ordovician unconformities are much less pronounced; and there is no evidence of appreciable Lower Paleozoic erosion. In this area the uppermost Ontelaunee Formation is evidently younger than any part exposed in central Berks County, and it may indeed, itself, be of the Lower Chazyan (lowest Middle Ordovician) age. Conformably or paraconformably overlying the Ontelaunee Formation is the high calcium Annville Formation of definite Chazyan Age. Prouty (1959), who provided the formal definition of the unit, claimed it to be Middle Chazyan separated by a Lower Chazyan hiatus from the Beekmantown Group. Hobson (1963) and MacLachlan (1967) find no compelling stratigraphic argument for this hiatus and see no physical evidence of it in the better exposures. If this interpretation is correct there is, strictly speaking, no such thing as a post-Beekmantown unconformity in the Lebanon Valley sequence. There is, however, a faunally established hiatus including all of Black River and possibly Upper Chazyan time between the Annville and the overlying Myerstown Formation.

The Myerstown and the overlying Hershey and Martinsburg Formations form a gradational and apparently continuous depositional sequence. The Hershey Formation is essentially argillaceous limestone but has an eastward thickening conglomeratic member in its lower part which contains primarily dolomite clasts which appear to have been derived principally or entirely from the Ontelaunee Formation. Clasts of Myerstown and Annville lithology are conspicuously absent in this member. While the Annville Formation is not exposed west of Womelsdorf in the main body of Lebanon Valley sequence exposures, the obvious immediate reasons for its disappearance are structural, and it recurs to the east in the Oley Valley outlier of Lebanon Valley lithologies. It, therefore, seems probable that the Annville Formation was an initial part of the sequence, now incompletely exposed for structural reasons, in the western part of the Sinking Spring quadrangle. Certainly the overlying carbonate formations extend all the way to the Hains Church fault, with tectonic interruptions, but with little change in general character.

Myerstown Formation (Lower Trenton)

Thin-bedded, medium-dark-gray, non-magnesian limestones stratigraphically above the Beekmantown Group in the vicinity of Wernersville were called Upper Annville Formation by Gray (1951) but were placed in the Myerstown Formation by Prouty (1959) when he provided a formal nomenclature for the Middle Ordovician carbonates of the Lebanon Valley. The Myerstown Formation is about 250 feet thick where fully developed in Lebanon County, lies disconformably on the Annville Formation and passes gradationally upward into the Hershey Formation. In the Wernersville area, the Myerstown Formation appears in patches in a complex fold and thrust structure. The crop width of the easternmost exposure would allow for a substantial fraction of the Lebanon County section but the internal structure cannot be resolved from existing exposure, and only a lesser part may be present. In any case, it has normal contacts with the overlying Hershey Formation but the lower limit of exposure is in each case delimited by thrusting.

The Myerstown Formation is predominantly a thin, regularly bedded, medium-dark to dark-gray, fine-grained, dense limestone, which weathers medium- to medium-light-gray with a distinct bluish cast. Its presence is often indicated in float by smoothly rounded plates of dense, ringing limestone. Very thin, dark shales are sometimes interbedded with the limestone. Lenses and beds up to about a foot thick of fossil fragmental calcarenite are not uncommon.

Four distinctive thin beds of pale-yellowish-orange to light-olive-gray, weathered, somewhat phyllitic shale, are widely distributed throughout the Lebanon Valley. Such beds are present in a few exposures in the Wernersville area, though it cannot be established that all four beds are to be found in this area. The lateral persistance of these beds and their anomalous character in the limestone sequence supports the assertion that they are metabentonites (altered volcanic ash falls). Similar metabentonites occur in the same general stratigraphic interval over a wide area beyond the Lebanon Valley, and they are considered excellent synchronous datum planes for stratigraphic correlation.

On the basis of a limited faunal and physical similarity to more fossiliferous strata in nearby areas, Prouty (1959) concludes that the Myerstown Formation is probably equivalent to the Upper Rockland and Kirkfield of the New York standard section and exactly equivalent to the "cement limestone" facies of the Jacksonburg Formation in the eastern part of the Lehigh Valley. MacLachlan (1967) disputes certain details of the physical and lithologic evidence for the precise equivalences of the latter correlation, but his objections have no substantial effect on the assigned age. The lower Jacksonburg is confined to the eastern part of Lehigh Valley exposures, and this was a time of non-deposition and possibly erosion in central Berks County.

The Myerstown Formation is very poorly exposed in the Sinking Spring quadrangle. The best exposures occur along U.S. Route 422 sporadically for 1500 feet west of the road to the Wernersville State Hospital (Figure 18).

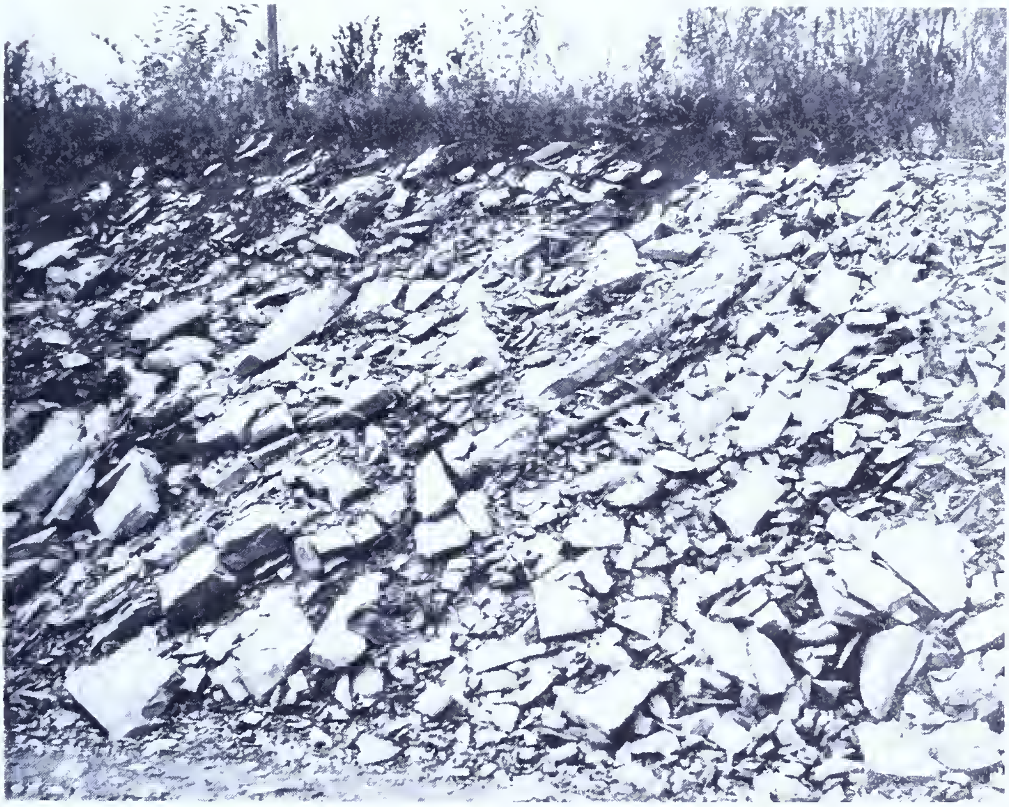

Figure 18. Myerstown Formation as exposed in fresh cut during construction of Route 422 north of Womelsdorf. These rocks are not comparably well exposed in the Sinking Spring quadrangle.

Hershey Formation (Middle Trenton)

Dark-gray, impure, shaly limestone (Figure 19) gradationally overlying the Myerstown Formation and grading upward into calcareous Martinsburg shale were mapped in Lebanon County (Gray and others, 1958; Geyer and others, 1958) following the recommendation of Prouty, who formally defined the Hershey Formation from a type section in Dauphin County (Prouty, 1959). The formal definition was shown by MacLachlan (1967) to be inconsistent with the mapping practice, and an amended definition was offered. From the vicinity of Myerstown, in eastern Lebanon County, eastward, the lower part of the Hershey Formation contains dolomite clasts apparently derived from the Beekmantown Group, probably mainly from the Ontelaunee Formation. The size and angularity of the clasts increases eastward as does the thickness of the conglomeratic member. East of Womelsdorf, exposure of the Hershey Formation is discontinuous owing to structural complications.

There is no doubt that patches of similar rocks, including the largest known blocks (greater than 6 feet) in the conglomeratic member, appearing west of the Hains Church fault (Figure 20) in the Sinking Spring quadrangle belong to the same stratigraphic sequence. Gray (1951) referred these rocks to the Jacksonburg Formation, but there appear to be excellent reasons for making formational distinction from rocks appearing in the Lehigh Valley (MacLachlan, 1967).

The Hershey Formation thickens eastward through most of the Lebanon Valley from 0 feet in central Dauphin County to perhaps as much as 1000 feet including possibly 250 feet of the conglomeratic member north of Womelsdorf (Gray, 1951). All the exposures in the Sinking Spring quadrangle appear to represent appreciably thinner sections, but none of these is complete.

In thrust slices in the Wernersville area the Hershey Formation is in contact with the Myerstown Formation, and conglomeratic material is well represented though apparently somewhat irregular in distribution. The stratigraphic top of the Hershey Formation is clearly absent for structural reasons around most of this area of Hershey exposure. Near

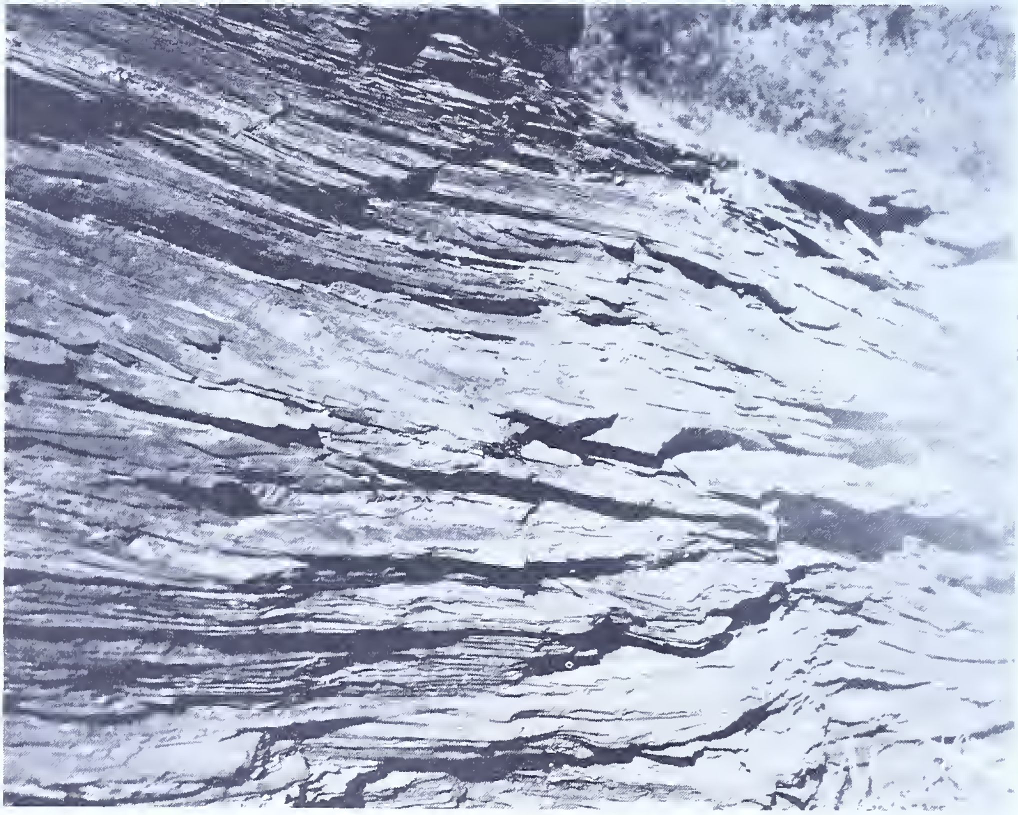

Figure 19. Typical shaly limestone of Hershey Formation in small tight folds.

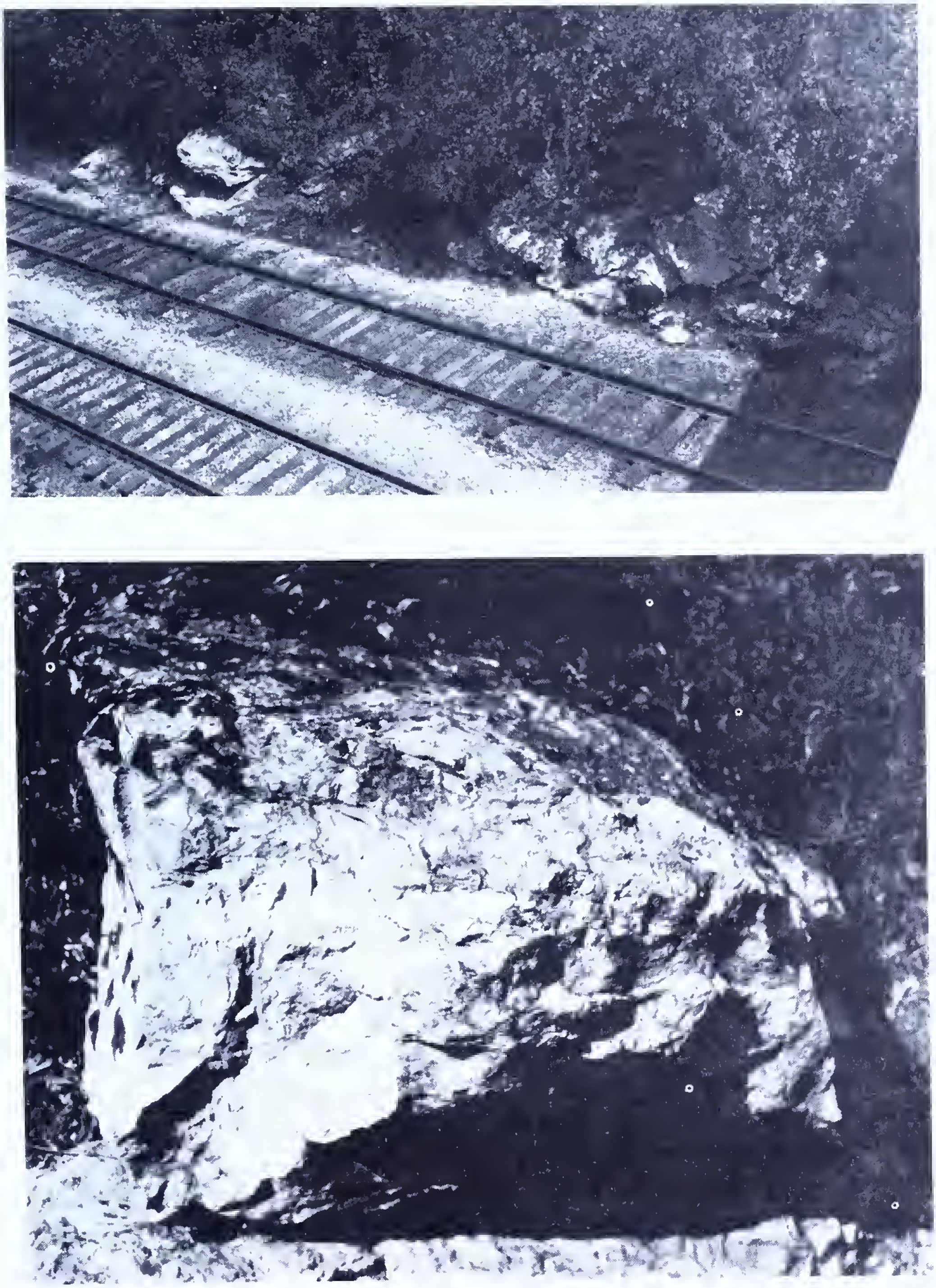

Figure 20. Conglomerate of Hershey Formation. Railroad cut near Wernersville State Hospital. Lower photograph is a close-up of the Hershey Formation.

the western edge of Wernersville, however, a patch of noncalcareous Martinsburg shale lies apparently in a synclinal core with obscure contact relations. The calculated thickness of the Hershey Formation lying between this shale and the Myerstown exposed in an adjacent anticline is somewhat less than 250 feet. As the Hershey-Martinsburg contact here shows no evidence of being gradational, it may be suggested that the shale is somewhat younger than basal Martinsburg and a local disconformity is present here. In this case, some erosion prior to deposition of the shale would be possible. Early thrusting at this locus cannot be excluded.

According to Prouty (1959) the Hershey Formation is Middle Trenton in age, approximately equivalent to the Sherman Fall of the New York standard section. He considers it precisely equivalent to the "cement rock" facies of the Jacksonburg Formation in the Lehigh Valley, though the latter may be slightly older at the base (MacLachlan, 1967) in the eastern part of the Lehigh Valley. The Jacksonburg thins westward toward central Berks County by becoming progressively younger at the base. During lower Hershey time some nearby Beekmantown terrane was actively shedding detritus; and it seems probable that the central Berks County area, which was certainly emergent at this time, was probably being actively eroded.

Good exposure of the Hershey Formation occurs in the Reading Railroad cut adjacent to the overpass to the Wernersville State Hospital. The oldest beds in the exposure are cut off by a thrust, but at least 50 feet of conglomeratic beds containing the largest dolomite blocks known in the formation and a larger thickness of the argillaceous limestone are represented. Elsewhere the formation is poorly exposed.

Jacksonburg Formation (Lower and Middle Trenton)

Dark-gray limestones with argillaceous layers to entirely argillaceous were recognized by the First Geologic Survey of Pennsylvania as a distinctive element in the Lehigh Valley between the heavy dolomite beds of the Beekmantown and overlying slates. These rocks were established as the Jacksonburg Formation by Spencer (1908) from a New Jersey type locality. It has been divided into a lower "cement limestone" and upper "cement rock" facies in the eastern Lehigh Valley which have been correlated (Prouty, 1959) with the Myerstown and Hershey formations respectively though it is not clear that precise equivalence has been established (Sherwood, 1964; MacLachlan, 1967). In any case, the base of the formation becomes progressively younger westward, and only the "cement rock" facies is represented in central Berks County.

Jacksonburg Formation in exposed contact with the Ontelaunee Formation is not present in the Sinking Spring quadrangle, though it may be found within a mile to the northeast in the vicinity of Leinbachs. Primarily on structural evidence, however, argillaceous limestones found grading upward into calcareous shale of the Martinsburg Formation in the western part of the quadrangle in a single thrust slice, are believed to be correctly referred to the Jacksonburg Formation.

The "cement rock" of the Jacksonburg Formation is essentially identical to calcareous shales of the Hershey Formation. They are fine grained, dark gray with pronounced cleavage and obscure bedding. Fresh cleavage surfaces are frequently shiny black and carbonaceous. Weathering causes the argillaceous limestone to disintegrate in gray or buff plates, which, however, seem to retain some reactivity to acid more persistently than the Hershey Formation. It might be suggested that the "cement rock" is a little more calcareous and carbonaceous, and a little less argillaceous than the Hershey Formation on the whole, but the distinction between them cannot be made by lithic field mapping criteria.

The Jacksonburg Formation of this thrust slice contains no suggestions of the dolomite conglomerate which is particularly prominent in nearby exposures assigned to the Hershey Formation. Inasmuch as the exposed Jacksonburg grades up into the Martinsburg, it may be argued that only the upper part of the argillaceous limestone section is exposed and no conglomerate is to be expected. It does, however, provide a distinct contrast with the nearby Hershey Formation exposures.

The distinction made here is clearly debatable on purely stratigraphic grounds, but the structural position and facing of the rocks in this thrust slice are such that they must have been derived from the Irish Mountain nappe. The Lehigh Valley sequence stratigraphy is thus most applicable.

Martinsburg Formation (Trenton to Upper Ordovician)

From Tennessee to southeastern New York State terrigenous clastic rocks, mostly gray shales with subordinate graywacke, overlying Middle Ordovician carbonates in the Great Valley are referred to the Martinsburg Formation (Geiger and Keith, 1891). These rocks form a great wedge of synorogenic deposits representing the flysch phase of the Taconic Orogeny. A modern regional summary of these rocks is given by McBride (1962).

In the area lying approximately between the Susquehanna and Lehigh Rivers, Stose and Jonas (1927) pointed out that an appreciable portion of the rocks were of atypical lithologies. Subsequent investigation showed that at a few localities it could be demonstrated there were faunal elements which were older than the top of the underlying carbonate sequence and could not have been initially deposited where they were discovered. Stose (1946) concluded that the lithologic and temporal anomalies arise from the fact that they occur in a major far-traveled thrust sheet of Taconic age, and he designated the exposed area of this supposed sheet the Hamburg Klippe. The implications of Stose's hypothesis received little immediate investigation; but recent and continuing work (Carswell and others, 1968; Platt and others, 1969; Myers, 1969; Alterman, 1969) support Stose in many substantial particulars. According to the recent work, the "Hamburg Klippe" is a distinctly recognizable terrane which was, at least approximately, correctly delimited by Stose. He designated the rocks in this area as the "Taconic Sequence" of Pennsylvania. The present investigation is too little concerned with the critical evidence to warrant extended discussion; but this designation does not seem apt, although it is clear that these rocks should be distinguished from the Martinsburg Formation. It is suggested that the local name Hamburg sequence is more appropriate, and it has been used in this report as the informal name for terrigenous clastics lithologically or stratigraphically distinct from the Martinsburg Formation.

At the time mapping was initiated the full significance of relationships between the Martinsburg Formation and the Hamburg sequence was not appreciated by the writer, and the clastic terrane was mapped by lithologies given arbitrary numerical designations. Lithic type 1 was assigned to shales most clearly related to normal Martinsburg Formation, and now comprises the entire exposure so identified. The remaining lithic types have been assigned to the Hamburg sequence and retain their numerical designations.

The terrigenous rocks underlying the northern fifth of the Sinking Spring quadrangle include only about one-fifth the width of the outcrop at this longitude and probably include a commensurate part of the total section. Purple or red shale and thin-bedded limestones occur in the northern part of this exposure. These were considered Taconic lithologies by Stose (1946) and included at the southern edge of the Hamburg klippe. He considered the rock lying south of the purple shale area to be normal autochthonous Martinsburg Formation. The interpretation of this report differs in that all clastics east of the Hains Church fault have been assigned to the Hamburg sequence. Apparently true Martinsburg appears only west of the fault in slices at the north side of the limestone valley and possibly in smears south of the main clastic belt.

A natural three-fold division of the Martinsburg Formation was asserted by Behre (1927, 1933) and reaffirmed by Drake and Epstein (1967) in the Lehigh Valley sequence of the eastern Pennsylvania slate district.

The latter subdivide the Martinsburg into three formal members which evidently persist westward into Berks County. The lower shale member (Bushkill) is evidently represented by the Sinking Spring occurrences and is discussed separately below. The medial, graywacke-bearing Ramseyburg member and the upper Pen Argyl shale members are not definitely recognized in the area of Hamburg sequence exposures, and it is doubtful that the eastern Pennsylvania subdivision is applicable southwest of Hamburg sequence exposures. Shales apparently autochthonous with respect to carbonate rocks of the Lebanon Valley sequence, however, are not evidently much different from the Bushkill Member and may reasonably be given this designation. The predominantly gray shales of lithic type 2 and the graywackes of lithic type 3 in the Hamburg sequence present an obvious analogy with the Bushkill and Ramseyburg Members respectively, and such a correlation may be warranted. Elsewhere in the Hamburg sequence, however, apparently similar shales contain graptolites of pre-Martinsburg age (Myers, personal communication) and Epstein (personal communication) asserts that Hamburg sequence graywackes and the Ramseyburg graywackes may be unambiguously distinguished by micro-petrographic criteria.

Bushkill Member

Dark-gray shale, certainly in part and probably entirely somewhat calcareous with little apparent silt and virtually no coarser detritus, is probably transitionally successional to the Jacksonburg Formation. It occurs in a structurally isolated sheet with the Hershey Formation west of the Hains Church fault (structural level C_1) and locally near the south margin of the next thrust sheet to the south (structural level C_2) where it apparently grades upward into noncalcareous, dark-gray shale. There is essentially no exposure of this rock except in the valley of Spring Creek, but its extent can be defined with reasonable confidence by the character of the overburden. Shale chips in the soil are smaller, weaker, and less abundant than in soils overlying shales elsewhere in the area considered typical of the Martinsburg Formation. This subtle but distinctive soil characteristic is believed to result from particular ease in disaggregation of weathered rock fragments after leaching of a carbonate component, and provides the basis for deducing that carbonate is a significant constituent throughout this rock. In exposures along Hains Mill Road by Spring Creek the rock at the south closest to the contact with the Jacksonburg Formation is sparingly calcareous, less so than much of the exposure and fresher float to the north. If this rock is the oldest exposed Martinsburg shale, a terrigenous clastic-rich pulse of sediment initiating the Martinsburg deposition in this area is indicated;

but there is a real possibility that the contact is tectonically disrupted, and that these rocks are not truly the oldest. Lying to the north of this zone, exposures for several hundred yards along the road indicate beds of silty limestone ½ to 2-inch thick forming locally up to 60 percent of the exposure. These beds cannot be traced away from Spring Creek in the float and have not been mapped as a separate lithology.

This part of the Martinsburg Formation is considered to represent deposits of the depostional phase initiated with the Myerstown and Jacksonburg Formations. During this phase there is a gradually increasing flux of fine clastic detritus into the carbonate depositional basin which was gradually deepening. The calcareous shales grade upward into otherwise similar but substantially noncalcareous, dark-gray shales. It is not clear whether a persistant carbonate component is merely swamped by increasingly rapid clastic influx or if some additional factor reduces carbonate deposition. Noncalcareous shales of the Bushkill Member are much like the predominant gray shales of lithic type 2 of the Hamburg sequence, but they seem to be somewhat less silty and entirely lack the varietal lithologies of the latter.

Throughout this report argillaceous rocks are frequently designated shales as a reflection of their depositional character, but low grade or incipient metamorphism is pervasive. The terms slate, phyllite, and meta-argillite would also be appropriate for the various lithologies. The Bushkill rocks are strongly cleaved, and, for the most part, obscurely bedded. The only persistent regular parting is cleavage which may be either fairly dull or glistening and sericitic on fresh surfaces. Bright cleavage partings in the calcareous Bushkill are superficially similar to carbonaceous cleavage partings in the Jacksonburg Formation, but can be readily distinguished. Upon weathering the Bushkill Member disintegrates to grayish-tan to buff cleavage plates. The plates from the calcareous shales are relatively fragile, but the purer shales yield fragments which seem to be fairly durable in tilled soils.

South of main shale belt a small patch of shale on the Hershey Formation west of Wernersville has been identified with the Bushkill Member though it is evidently part of the Lebanon Valley sequence. Other occurrences are more problematical. Shale appears in the core of the Wyomissing syncline from the east border of the quadrangle discontinuously to the west side of Sinking Spring Borough. Known exposures within the quadrangle would not preclude assignment to the Bushkill Member, but varietal lithologies and evidences of the Lorah thrust in the Reading quadrangle indicate that these are Hamburg sequence rocks. Phyllitic shale again appears at the south side of the carbonate valley in patches formed by slices in the Grings Mill-Shillington thrust system.

No definite Hamburg sequence lithologies are known to occur here but exposure is negligible and the original position of the rocks is uncertain. With the intention of restricting the Hamburg sequence as much as possible to its type area the rocks have been tentatively assigned to the Martinsburg Formation. The same occurrence is thought to be represented by "slate" which has been exposed to the thermal effects of a major Triassic diabase intrusion, and is found as float above the old Ruth Mine of the Wheatfield district. Spencer (1908) reports exposure in pits at the time of his examination and reports a thickness of about 80 feet. Similar occurrences of "Paleozoic slate" above the mineralized limestone are mentioned in early reports (d'Invilliers, 1883; Spencer, 1908) at several mines in the area for which there is no present surface indication.

Hamburg Sequence

The Hamburg sequence was essentially defined by exclusion in the Martinsburg Formation description. It consists of those rocks in the Great Valley "shale" belt originally noted by Stose and Jonas (1927) which are in large part lithically distinct from typical shales and graywackes of the Martinsburg Formation and at least in part faunally older. It is substantially identical with the "Taconic sequence" of Stose (1946) but the local name is not intended to imply certain correlations and age assignments suggested by Stose which are not supported by available faunal evidence. Rejection of the name "Taconic sequence" does not imply that these rocks are not related to the Taconic orogeny in origin and emplacement, which is almost certainly true. However, these rocks appear to be less closely related to the rocks of the type Taconic area in northern New York and Vermont than is implied by the name and Stose's correlations.

The Hamburg sequence consists of a diverse assemblage of lithologies including some not represented in the Sinking Spring quadrangle. In this area they have been mapped as six lithic types (or assemblages) and several subtypes which have been rather arbitrarily assigned numbers 2 to 7, lithic type 1 having been assigned to the Bushkill Member of the Martinsburg Formation. The numbers bear no relation to stratigraphic or tectonic superposition, but in some measure reflect a subjective degree of strangeness with respect to typical Martinsburg lithologies.

Contact relations between the Martinsburg Formation and elements of the Hamburg sequence have not been established through its full extent. A tectonic model is presented elsewhere in this report. In the Sinking Spring quadrangle, and probably at least throughout Berks County, Stose's Hamburg klippe appears to be a real entity in which a previously formed complex of early thrust or slide slices was emplaced substantially as a unit in or on the Martinsburg Formation of the Lehigh Valley sequence prior to major deformation of the Irish Mountain nappe.

Seven or eight distinct tectonic levels have been recognized in the Hamburg sequence (Myers and Wood, personal communications). Two or possibly three of these are present in the Sinking Spring quadrangle. Some lithic types are characteristic of particular levels, others occur at several levels with different associations. It is not clear whether these repetitions represent elements of the same age and provenance. In any case it should not be supposed that the term sequence is intended to imply any established stratigraphic succession.

The age of the Hamburg sequence has not been established by direct evidence in the Sinking Spring quadrangle. The tectonic model would suggest that some part of it might be contemporaneous with the Martinsburg Formation, but a growing though scattered accumulation of graptolite and conodont assemblages (Stose, 1946, Alterman, Epstein, Myers, and Riva, personal communications) give ages which are certainly older than Martinsburg to no younger than lowermost Martinsburg. All reasonably certain ages, however, are Ordovician and probably post Canadian. Cambrian rocks equivalent to those in the type Taconic area do not seem to be present as claimed by Stose.

Predominantly Gray Silty Shales (Oh2)

In fresh exposures these shales are ordinarily medium-dark to dark gray. They are variably silty and may contain silty bands which define bedding, though this feature is less commonly observed where the rock is strongly cleaved as in this area. In parts of the area mapped as composed of this lithotype, exposures may show occasional thin coarser bands of graywacke but this material is not sufficiently abundant to be evident in the overburden. This absence of graywacke fragments in the float is the essential mapping criterion distinguishing it from the shale and graywacke rocks, lithic type 3. The lighter-gray shales in this area are sometimes distinctly greenish, but clearly distinct from the green rocks in lithic types 4 and 5. The greenish-gray shales of this lithotype are often conspicuously phyllitic.

The shales weather readily to grayish yellow or buff, rarely with a pinkish cast. Fresh shale is commonly encountered only in substantial excavations and occasionally in stream beds. Weathered shale *in situ* is usual in shallow excavations and may be encountered as deep as 50 feet in wells.

Small scattered patches faint purplish-gray to distinctly grayish-purple shale have been included in this lithic type. Larger mappable bands of purple shale in a gray shale matrix have been separated and included with lithic type 5, although they are probably not identical with the purple shale and green shale assemblage which forms the major crop area identified as lithic type 5. These shales tend to retain the purple color even with substantial weathering.

Thin-bedded limestones are intimately associated with gray shale more commonly than other lithic types but these have been segregated as lithic type 6. Contact relations suggest a high degree of structural complexity which may be most explicable if some of the irregularities were developed by processes approximately synchronous with deposition. Rocks of this type appear on both sides of the Hains Church fault, although structural continuity is evidently interrupted. There is no basis for deducing major offset across the fault in this area.

South of the main shale belt, shales of lithic type 2 occur as isolated patches infolded in the core of a syncline. Definite evidence that these are not Bushkill Member has been found only in the Reading quadrangle, but the structurally simplest interpretation would place them in any case above the Lorah thrust.

Shale and Graywacke (Oh3)

Much of this lithic type is composed of shale indistinguishable from that of lithic type 2. It contains, however, variable amounts of interbedded graywacke from less than an inch to over a foot thick. In the best exposures of this lithic type along Spring Creek south of Brownsville and along the road about a quarter mile east, it appears that several graywacke-rich and shale members of substantial thickness could be distinguished, but they cannot be traced in the float even between these exposures. While the members could be mapped by projection along strike with fair reliability in this vicinity, it seems pointless as there appears to be no prospect of extending the mapping into the remaining area of poor exposure. The normal contact with lithic type 2 is gradational and some thin graywacke beds occur in rocks so mapped. In the area of lithic type 3, however, graywacke is everywhere sufficiently abundant that weathered fragments are present and usually conspicuous in the soil. This soil character is an effective and sufficient mapping criterion for defining the terrane of lithic type 3.

Lithic type 3 is typically a sequence of alternating dark-gray shale and light or medium-gray, light-brown to yellowish-brown weathering, graywacke and graywacke siltstone. The graywacke forms up to about a third of the rock in zones where it is abundant and is essentially absent in intervening zones on the scale of 100-200 feet. Graywacke may not much exceed 10 percent of the lithic type as a whole. Typical graywackes are fine to medium grained. Sand size particles are more than half quartz but also include rock fragments and altered feldspar (?). Grains are commonly subangular to sometimes subrounded. Fine matrix is commonly more than a third of the rock.

Graywacke is more conspicuous, probably more abundant, and certainly includes coarser-grained material in an area which is interpreted to lie in a slice in the State Hill thrust zone. The differences between these rocks and those previously described seems sufficient to segregate them as a distinct lithic subtype 3a. This area contains at least one, and probably more, beds with very coarse sand to granule-size quartz fragments in a brownish (weathered) matrix. In addition, a very poorly-sorted, conglomeratic graywacke exposed only in a few crops on the bank of Tulpehocken Creek, contains black shale plates and rounded limestone cobbles up to about 10 inches in maximum dimension. Greenish-gray phyllitic shale of the type mentioned in the description of lithic type 2 seems particularly abundant in this area. As distinct from typical lithic type 3, which does not seem to be topographically distinguishable from surrounding rocks, lithic type 3a appears to be somewhat erosionally more resistant and underlies the ridge at State Hill.

A second distinctive lithic subtype, 3b, has only a single small outcrop; but its distribution is marked by a distinctive soil with abundant pebbles and cobbles of fairly coarse, clean graywacke and there are no visible shale chips as is almost everywhere else a conspicuous coarse soil component associated with the clastic terrane. The inference is that lithic type 3b is essentially all graywacke. The map pattern indicates that the graywacke forms a single body whose upper (northern) contact is appoximately parallel to the strike of the single attitude determined within it and the trend of surrounding beds. The lower contact is convex southward and truncates turbidite beds of lithic type 3. The form of the body clearly suggests a channel fill. The depositional environment of the enclosing and overlying beds strongly argue against subaerial erosion. It seems probable that the channel was scoured by turbidity currents.

Yellowish to brownish silty rock found at a few exposures west of Brownsville was lumped with lithic type 3 as essentially a fine-grained graywacke. These rocks probably in fact represent a distinctive buff siltite unit which is widespread north of the Sinking Spring quadrangle (Myers, work in progress). Its presence here may reflect some structural complication beyond that indicated by the present mapping. If so, it is doubtful that it can be resolved under the existing conditions of poor exposure.

Shales and graywackes of lithic types 2 and 3 in the Sinking Spring quadrangle are limited to and largely constitute a discrete tectonic level of the Hamburg sequence. According to Myers (personal communication) this is the sixth highest across the strike of the clastic belt at this longitude.

Green Phyllitic Rock (Oh4)

This enigmatic unit is easily mapped on the basis of its distinctive float. Soil in this area contains abundant irregular fragments weathered to a unique pinkish-orange color. The fragments are approximately equant in contrast to the pronouncedly platy habit of soil fragments characteristic of all argillaceous rocks. Freshest exposures along the road south from Brownsville show a dark-grayish-green colored silty argillite with abundant fine micaceous material (chorite?). X-ray diffractometer analyses of these rocks show essentially the same mineral composition as normal shale of lithic type 2 with a somewhat high proportion of 14 and 7 Angstrom "clay" minerals which would include the visible chlorite (?). Much of the rock is apparently structureless with rather irregular parting, but there is at least one zone with a "hash" of slightly lighter, somewhat more siliceous, inclusions. These inclusions, on close examination, apparently represent remnants of sedimentary layers which were jumbled and folded after disruption. This disturbance is entirely unrelated to the rather poorly defined cleavage in this rock, and it is evidently the result of early deformation or slumping in a poorly consolidated state.

Lithic type 4 occurs at the same structural level as lithic type 3a, forming a distinct slice in the State Hill thrust zone. Lateral relations between 3a and 4 are obscure. The State Hill thrust is an early deformational feature, as evidenced by obvious folding of the thrust surface and probable prelithification deformation in lithic type 3a, as well as by the thrust sequence deduced by geometric relationships. Dark-green silty rock, somewhat comparable to lithic type 4 but less disturbed, is exposed north of the Sinking Spring quadrangle where it occupies and essentially constitutes a discrete tectonic level, the fourth highest in the Hamburg sequence at this longitude according to Myers (personal communication). If the Sinking Spring occurrence is the same rock, its tectonic position is anomalous.

Purple and Green Shale (Oh5)

Grayish-red purple shale chips are abundantly scattered through the soil of an area extending eastward from Brownsville to the northeast corner of the quadrangle, usually with an abundant admixture of ordinary looking weathered buff shale chips and sometimes conspicuously greenish ones, but in some areas only purple is found. Numerous small exposures encountered along most roads traversing the area show that the purple shale may occur in thick units but is often intimately associated with fairly light, clear-green shale which appears bluish to some observers (Figure 21). Beds which look like buff weathered normal lithic type 2 shale are also abundant but attracted little attention in the field. Extensive drilling in the vicinity of Blue Marsh shows that the buff color is that of the fresh rock and that normal lithic type 2 gray shales are rare. Comparison of fresh and weathered materials shows that the color of the buff shales is unchanged; the green shale tends to fade and weather to buff chips, but much less rapidly than lithic type 2 gray shales; and the purple shales weather buff very slowly though the color is largely lost in the finer soil particles.

The contact between this lithic type and underlying Beekmantown Group carbonates is well exposed only outside the main outcrop area at a small abandoned quarry about 3300 feet southwest of State Hill. At this point and several others south of the main exposure area, purple shale is

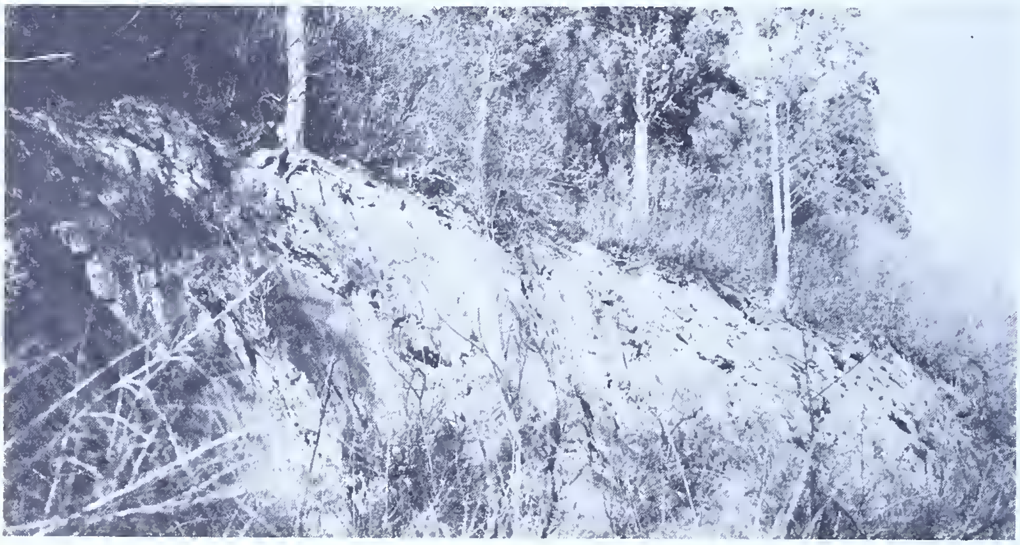

Figure 21. Cut in purple and green shale of Hamburg Sequence lithic type 5. Color contrast, which is not conspicuous in the photograph, shows bedding dipping to the right (south) less steeply than the more obvious cleavage. Bedding attitude is comparable to carbonates in the quarry nearby and the shale appears to rest disconformably on the carbonates. Relatively fresh exposures of the gray shale of lithic type 2 appear similar to this black and white picture. The latter tend to become weathered buff and crumble to platy debris in a few years.

preserved as a thin screen in the Lorah thrust zone. The rock is, of course, strongly sheared and original contact relations are obscure. In the main crop area, attitudes of probable bedding define a fold structurally conformable with that established in the Beekmantown Group tongue which projects just across the north edge of the quadrangle.

Moseley (1949) attempted to map the fold in the shale by tracing distinct "red" beds through the area of lithic type 5. Present mapping finds no evidence of such persistent beds.

Purple and green shales seem to interfinger along strike in quite a complex manner. This impression is confirmed by the drilling data where correlation between quite closely spaced holes seems uncertain.

Glaeser (personal communication) suggests that a tidal flat enviroment seems most probable for this sediment. The variation between purple and green evidently reflects the oxidation state of iron in these otherwise identical shales and may reflect very subtle changes in relief of the tidal flat. The implications of a tidal flat assemblage in the Hamburg sequence has not been fully explored, but it points to existence of tectonic lands to the south or southeast during the Ordovician.

Scattered occurrences of lithic type 5 as identified by the presence of purple shale occur outside the main exposure belt. Green shales in these areas are either lacking or not recognized in the prevailing poor exposure conditions. South of the main belt they are associated with the trace of the Lorah thrust. The most southerly of these remnants is only a mile from lithic type 2 shale laying on the Ontelaunee Formation preserved in a synclinal core. There is no substantial thrust between, but the distance along the bedding surface across the intervening anticline could well be twice as great. The purple shale is not apparent at the base of the synclinal outlier in the Sinking Spring quadrangle but has been encounttered locally in the Reading quadrangle. Northwest of the main exposures purple shale is associated with limestone surrounded by lithic type 2 shale. The relation between the purple shale and limestone will be considered in the next section.

Elsewhere pinkish to distinctly purple shale has been sparingly found locally in lithic type 2 shales but not with comparable shale of lithic type 3 graywacke-bearing rocks. These occurrences are not mappable and of uncertain signficance.

Traces of purple shale and somewhat similar but probably unrelated red or maroon shales are found at several places within the Hamburg sequence. The widespread purple and green assemblage, however, is limited to and characterized by a single structural level in the Hamburg sequence in and near the Sinking Spring quadrangle. It is the fifth highest at this longitude according to Myers (personal communication).

Thin-bedded Limestone and Shale (Oh6)

The usual form of this lithic type is characterized by dark-gray, aphanitic limestones, weathering light gray with a bluish cast, in ¼- to 2-inch beds with somewhat subordinate interbedded dark-gray shale. In some areas, apparently continuous along strike with more typical rock, the limestone has been broken into a sharpstone breccia with a sandy lime matrix.

The principal exposure of this lithic type is in a belt entering the north edge of the quadrangle through its central part. The belt has predominantly gray shale of lithic type 2 adjacent on both sides. The thickness indicated along most of the belt is probably in the neighborhood of 300 feet, though some appreciable part of this appears to represent a dark-gray shale zone included between an upper and lower limestone in some areas. Elsewhere float suggests the limestone is more continuous. Two limestone zones are definitely indicated for a distance on the west side of the Hains Church fault; but it is not clear whether these are the same as indicated further east, or whether the clearly separable thin zone on the west is a third local zone.

Very limited scattered indications of small zones of thin-bedded limestone are conceivably at a single stratigraphic level in the main exposure of lithic type 5. Autochthonous appearance of this lithic type may be consistent with a supposed mud-flat environment if we suppose they accumulated in sheltered lagoons with restricted circulation, and probably hypersaline, euxinic environment. Otherwise one is inclined to suppose that they represent a relatively deep-water carbonate facies. Elsewhere in the quadrangle the limestone appears only as fragments associated with graywacke float in what is thought to be a thrust zone complex.

Elsewhere in the Hamburg sequence limestone comparable to lithic type 6 is widespread in distinct zones which disappear abruptly along strike. Platt (in Carswell and others, 1968; Platt and others, 1969), particularly has identified a number of these zones which extend up to more than half a mile as discrete exotic slices which slid into the shale during deposition. In at least one occurrence in Dauphin County the rock is faunally older than the enclosing rock and possibly contemporaneous with the Beekmantown Group. "Red" shale is associated with apparently exotic limestones and is also believed to be allochthonous with respect to enclosing shales.

The peculiar contact relations between the limestone belt at the north edge of the quadrangle and two associated belts of lithic type 5 purple shale are clearly not reconcilable with any simple depositional model, though the belts conform to the general trend of the enclosing shale. It appears that the lithic type 5 and 6 rocks may well represent exotic slices.

Quartz Conglomerate (Oh7)

Nearly white to light-tan quartzose fragments up to about 2 inches in size and subordinate lithic fragments, both poorly sorted and quite angular, and fairly tightly packed in a brown, fine-grained matrix occur only as float on the crest of two hills north of Pendergast Road. The float is bouldery and conspicuous (Figure 22). The larger area of float is elongate parallel to the trend of surrounding rock and the smaller area of float continues the trend indicated by the larger. No indication of the rock is found on lower ground between the two areas. The surrounding rock appears to be normal lithic type 2 gray shale. The rock is evidently preserved only in the core of a syncline which has elsewhere been eroded to a lower stratigraphic level. Thinly scattered float, apparently related to this lithic type but with particles rarely exceeding granule size, occurs over a fairly wide area including carbonates to the south. These are evidently derived from Quaternary erosion of a formerly greater extent of these rocks.

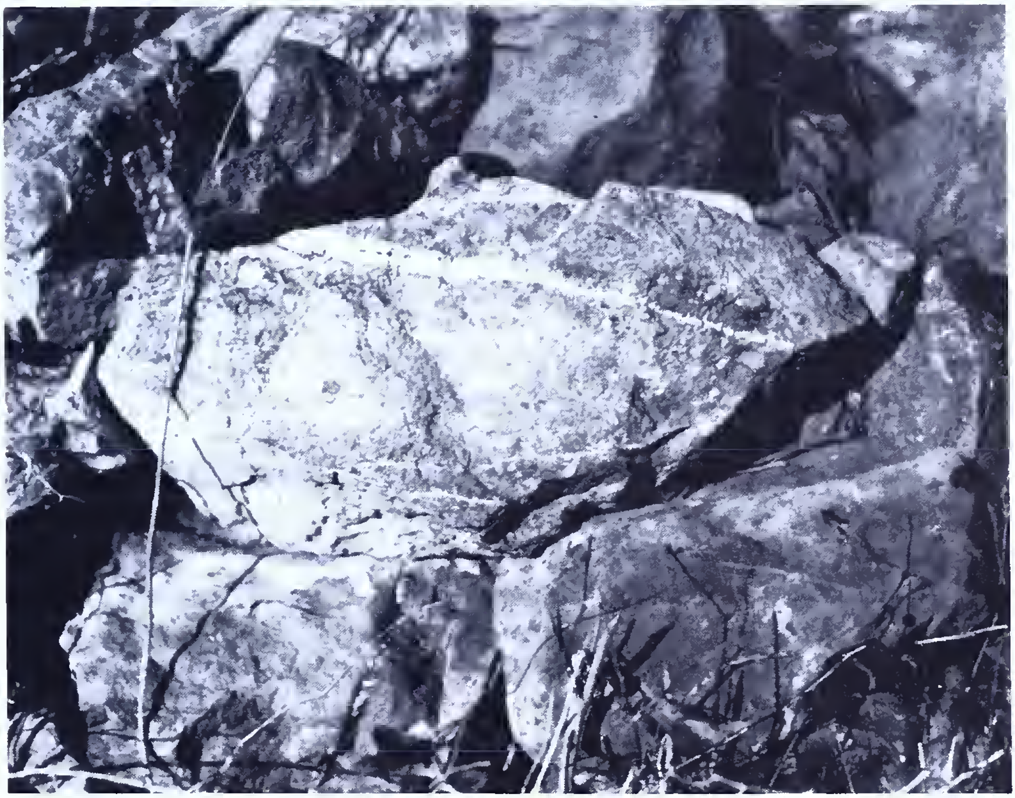

Figure 22. Boulder of quartz-lithic conglomerate of Hamburg Sequence lithic type 7. Block occurs in debris cleared from field on the north side of Pendergast Road. Block at lower right is boulder of diabase from Triassic dike present in this area.

Triassic Rocks

Two dikes of fine-grained diabase extend for several miles through carbonate rocks of the Sinking Spring quadrangle, presuming discontinuous exposure may represent a feature continuous at depth. A third shorter section appears south of the largest dike that cuts through Sinking Spring Borough. These dikes appear to be identical to dikes cutting Triassic sediments which are nonetheless generally agreed to be of Triassic age. A specimen of the long dike near Sinking Spring Borough has been included in a regional study of Triassic intrusives (Smith and Rose, 1970). It is chemically identical to Rossville type intrusions of the Triassic sediments (Smith, personal communication).

Triassic sediments lie unconformably on Paleozoic formations previously described in the Wheatfield area of this quadrangle and on rocks of the main Great Valley belt only a few miles east and west of the quadrangle. They are stratigraphically successional to Lower Paleozoic carbonates and shales in this area. The Triassic rocks are considered in detail in a separate chapter of this report.

Surficial Deposits

Through most of the quadrangle the bedrock is mantled by indigenous soil and weathered material which may reach considerable thickness, especially in carbonate areas. The soils have been recently mapped in detail (Ackerman, 1970) and that work is duplicated here only to the extent of showing the distribution of signficant areas of transported material in the form of alluvium and quartzite-gneiss colluvium.

Except along Tulpehocken Creek in the northern part of the quadrangle the alluvial materials have an obvious relation to adjacent or nearby rock units and probably represent no substantial volume or thickness. The alluvial zone along Tulpehocken Creek is typically less than 200 yards wide, but, at least locally, it may exceed 20 feet in thickness. No significant lenses of sand or gravel are known in these deposits but scattered pebbles and cobbles include lithologies which must have been transported substantial distances.

Under prevailing climatic conditions downslope movement of unconsolidated and broken material is general though not usually rapid. Sheetwash and rilling as well as the cultivation itself may be significant factors on cultivated slopes, but creep and frost heave appear to be the principal mechanisms on permanently vegetated slopes. All of these processes except cultivation were probably more active under the periglacial conditions of the Pleistocene. At some point depending on definitions this shifted material is properly colluvial rather than strictly residual but the distinction is usually not significant for most purposes unless the material is moved over a substrate distinctly different from its source.

As topography of this area is largely a function of bedrock lithology, it is common for soils at the base of slopes to contain fragments of upslope derivation which differ from local bedrock. The amount of such material depends on the length and steepness of the slope. There are many local examples of this type comprising a number of different combinations of allogenic clasts and substrate, but in most cases they are not volumetrically significant and do not differ importantly in environmental characteristics from the normal residuum. No effort has been made to delimit these minor occurrences here though some can be deduced by comparison of the soil map (Ackerman, 1970) and the geologic map, notably in the distribution of limestone- and shale-derived soils compared to the distribution of limestone and shale bedrock in the northern part of the area.

The greatest topographic break lies between the quartzite and gneiss of South Mountain and Grings Hill and the carbonate floored valley. Gravelly silt containing abundant pebbles, cobbles, and some boulders of quartzite and subordinate gneiss form an extensive blanket over the carbonates north of these hills which is shown by an overprint pattern on the geologic map. A few bedrock exposures, sinkhole collapse areas, excavations, and wells show that throughout much of the area the colluvial deposit is less than 20 feet thick, even immediately adjacent to the hills, but substantially greater thickneses may be expected locally. Colluvium in excess of 80 feet was apparently penetrated just west of the area in Robesonia.

STRUCTURE

Introduction

The structure of Paleozoic rocks in the Sinking Spring quadrangle is the complex result of several episodes of folding and thrust faulting related to two major orogenic epochs. The earlier epoch culminated in nappe structures of Alpine style and proportions which are the dominant elements in the present pattern. The writer no longer retains any doubts that the nappe formation is to be identified with the Taconic orogeny (Upper Ordovician) though a complete review of the stratigraphic, structural, and radiometric evidence is beyond the scope of this report. The later deformation is obviously identified with the Late Paleozoic Alleghanian orogeny which produced the folds of Ridge and Valley province to the north.

During the Taconic, rocks of the Great Valley, from a point somewhat west of the Susquehanna River and extending beyond the Delaware River, occupied a relatively external zone of an Alpine-type orogeny which was characterized by superposition of series overfolded and thrusted nappes comprising only slightly metamorphosed rocks of miogeosynclinal or shelf facies and their continental basement. Nappe structure in the Lebanon Valley was first explicitly recognized by Gray (1959) though the name Lebanon Valley nappe formally appeared later (MacLachlan, 1967). Only the lower limb of the Lebanon Valley nappe was definitely identified in its type area and its rocks are continuous into the western part of the Sinking Spring quadrangle. Rocks of the upper limb are apparently present in the Womelsdorf quadrangle (Geyer and others, 1963); but they have only now been identified as such on the basis of continuity with better exposure to the east in the Sinking Spring and, more importantly, Reading (MacLachlan, work in progress) quadrangles.

Concurrently with the Lebanon Valley investigation, Drake and co-workers (various papers 1960-1970) established that the crystalline rocks of the Reading prong and contiguous Cambo-Ordovician sediments near the Delaware River composed a major rootless nappe which they named the Musconetcong nappe (Drake and Epstein, 1967). The aeromagnetic map of Southeastern Pennsylvania (Bromery and Griscomb, 1967) leaves no doubt that the same character of deformation extends westward at least to the limit of continuously exposed crystalline rocks in the vicinity of Reading. Crystalline rock exposed in Irish Mountain, north-northeast of Reading, with conformably enveloping Lower Paleozoic sediments of the Lehigh Valley sequence are here designated as lying in the Irish Mountain nappe. This nappe apparently does not include all crystalline rocks of the prong in the vicinity of Reading. An extension of the Sinking Spring thrust enters the prong near Frush Valley and crystalline rocks south of this thrust belong in a different tectonic level, probably the Lebanon Valley nappe. Present indications are that the Irish Mountain nappe extends eastward along the north edge of the Reading prong to the vicinity of Hellertown where it overrides the Musconetcong nappe (Drake, personal communication). Magnetic data indicate that the crystalline rocks terminate near their exposure in Irish Mountain, but the nappe fold in the sediments extends westward into (but not necessarily much beyond) the Sinking Spring quadrangle. Most of the Paleozoic clastics and some of the carbonates of the quadrangle are associated with the upper limb of this structure.

Pelitic rocks of the Martinsburg Formation and Hamburg sequence occupying the northern part of the Great Valley form the envelope of the nappe system. The contact between the carbonates and shales is an obvious locus of detachment, but adjacent to the carbonates the shales are constrained to conform with major buckles in the more competent rocks and can deform only semi-independently during nappe formation. In this situation the shale is identifiably associated with a specific carbonate nappe and may be transported a substantial distance with it. Passing away from the carbonate contact the shales deform more independently and individual nappes cannot be definitely recognized. Rather the shales seem to form an envelope to the nappe system as a whole, into which the individual nappes were emplaced, and thus constitute a distinct tectonic level.

In terms of the carbonate nappe emplacement, which is perforce the principal concern of structural analysis in the Sinking Spring quadrangle, the rocks of the Hamburg sequence may be treated simply as an element of the pelitic envelope, here largely involved with the Irish Mountain nappe. They do, however, present problems and information concerning phases of the Taconic orogeny antecedent to the carbonate nappe emplacement which must be largely resolved outside this area. Immediately north of the Sinking Spring quadrangle, Myers (in preparation) has established a sequence of seven early formed thrust or slide slices in the Hamburg sequence, each characterized by a distinctive lithic assemblage. This sequence was transported on or into the Martinsburg Formation in its present relative position prior to nappe emplacement as a complex unit essentially identical with the Hamburg klippe of Stose (1946). In and near the Sinking Spring quadrangle the fifth and sixth highest of these Hamburg sequence slices rest on the Beekmantown Group of the Irish Mountain nappe on the Lorah thrust. This thrust certainly was an active detachment surface between the pelitic and carbonate rocks during nappe emplacement, and it may be that it originated at that time. It was noted in the stratigraphic description, however, that earlier movement at this horizon would help to account for the irregular distribution of the Martinsburg and Jacksonburg Formations in this area. If this interpretation is correct, the Lorah thrust is then the thrust at the base of the Hamburg klippe and equivalent to the "Taconic thrust" of Stose.

Earlier history of the Hamburg sequence will probably remain largely conjectural, but a coincidence too striking to be plausibly coincidental provides a basis for an evolutionary model. As the writer has refined his understanding of the distribution of the rocks to be identified with the Hamburg sequence and carbonates of the Lebanon Valley sequence, he has observed that their limits along the trend of the Great Valley are precisely coincident. This does not imply that both are presently part of the Lebanon Valley nappe. Indeed, it was previously observed that Hamburg sequence is more intimately associated with the Irish Mountain nappe in the Sinking Spring area. Rather it suggests that the Hamburg klippe and the Lebanon Valley nappe share a common stage of evolution. Both by superposition and stratigraphic criteria the Lebanon Valley nappe is of somewhat more southern tectonic provenance than the Irish Mountain nappe; and, in the ordinary sequence of Alpine-type orogenesis, it would be affected sooner. The suggestion is that the Hamburg klippe was detached from the cover of the Lebanon Valley nappe at a relatively early stage in its evolution, and advanced to its present position relative to the Martinsburg Formation before (or as) nappe generation progressed into the area of the Irish Mountain nappe.

The Hamburg sequence cannot have been derived intially from the Lebanon Valley nappe because it is at least in part older than indigenous rocks of the Lebanon Valley sequence. That is to say that part of the very substantial transport required to superpose contemporaneous slope or abyssal shales and inner shelf carbonates is accounted for, but the facies problem remains. Obviously if the trick works once, however, it may be done again, with the extremely allochthonous rocks essentially riding the front of an advancing wave of orogeny in what has been called the "surf riding principle in tectonics" (Zwart, 1963).

In the Sinking Spring area the major structural grain defined by typical bedding attitudes except near the hinges of plunging folds and small scale deformational structures is roughly east-west. Southerly dips, characteristically about 20 to 50 degrees, predominate over about 80 percent of the area, but a major portion of recorded dips represent overturned strata. The dominant deformation mode is thrust faulting from the south or southeast which commonly emplaces older on younger strata. Despite the predominance of southerly dips, the combined effect of the thrusting and the prevalence of overturned beds is to expose progressively older rocks southward from the Middle Ordovician shales to the Precambrian gneisses, though there are reversals in the trend resulting from folding. The gross section is thus overturned though it contains upright elements.

Cambrian and Precambrian rocks occupying approximately the southern third of the area of Pre-Triassic outcrop are emplaced on Alleghanian thrusts which dip gently southward and truncate a complex of older structures. The rocks of these thrust plates had been previously folded and are shown by the carbonate stratigraphy and orientation to have been derived from the upper limb of the Lebanon Valley nappe.

The trace of the thrust below the Alleghanian plates is against the Beekmantown Group across the quadrangle, but these are overturned rocks of the lower limb of the Lebanon Valley nappe in the west and upright rocks of the upper limb of the Irish Mountain nappe in the east. Along strike these major units are presently separated by a late, high-angle fault, but the fundamental structure is nappe emplacement of the Lebanon Valley lower limb above the upper limb of the Irish Mountain nappe. This relationship is apparent along the north edge of the

Lebanon Valley belt where it overrides rocks of Irish Mountain affinities in a complex of slices. General movement of both nappes is Taconic and essentially synchronous. Thrusting of the Lebanon Valley nappe on the Irish Mountain nappe might imply that movement of the former persisted somewhat longer, but the same effect could have been produced by interference between the two nappes during their mutual advance. The area of exposure is insufficient to prove the generalization within the quadrangle, but folds of the scale mapped in the Lehigh Valley sequence rocks in the eastern part of the quadrangle do not occur anywhere in the Lebanon Valley. The Lebanon Valley sequence rocks tend to be more strongly sheared and obviously recrystallized than their Lehigh Valley sequence counterparts. These differences lend a somewhat different aspect to exposures in the two terranes, which may be characterized as a difference in structural facies. The distinct structural facies owe their character to the contrasts prevailing between the upper and lower limbs of major nappes.

The structural aspect of areas underlain by shales in the northern part of the quadrangle and the argillaceous limestone of the Hershey and Jacksonburg Formations differs appreciably from that of the older carbonates. This difference is apparent regardless of structural level and reflects differences in tectonic response in materials of different mechanical properties. With the exception of possible pretectonic deformation of the shales, the difference in structural aspect does not necessarily represent a fundamentally different tectonic history. Taconic cleavage rather than bedding is the most prominant surface in these rocks, and the effects of the Alleghanian deformation are more conspicuous than in the more competent carbonates.

The main body of shales in the envelope of the Musconetcong nappe is detached from the underlying carbonates by the early Lorah thrust and equivalent feaures in some other areas. Their Taconic deformation seems to be semi-independent of Taconic folding and thrusting in the core and carbonate mantle of the Musconetcong nappe on a regional basis. South of the Leinbachs thrust, however, exposed shales overlie the folded Lorah thrust at no great depth and the major pattern of shale deformation is constrained to conform with that of the underlying carbonates. North of the Leinbachs thrust the Lorah thrust drops to appreciable depth and may pass into general crumpling at the brow of the nappe if it originated during nappe emplacement. In this area the direct influence of the folds in the carbonate rocks is absent or dies out northward.

The regional strike of both the Irish Mountain and Lebanon Valley nappes is obvious enough on the State Geologic Map, and it differs little in the Lebanon and Lehigh Valleys. Regional movement of the nappes obviously cannot have deviated very much from perpendicular to the regional strike. This movement direction is only a few degrees different than the regional direction of maximum Alleghanian compression implied by the regular trace of Alleghanian folds in the Ridge and Valley Province to the north. It is obvious that, in general, structures attributable to Taconic and Alleghanian folding will not be distinguishable by strike, if distinguishable at all (e.g., Drake, 1969, p. 115). In and around the Sinking Spring area, however, Taconic trends seem to have been initially variable owing to the proximity to the end of the Irish Mountain nappe and perhaps some retardation of the Lebanon Valley nappe by mutual interference at their conjunction. Strike discordance between Alleghanian structures, which persist in the regional trend, and Taconic structures, therefore, can be demonstrated locally. Reorientation of Taconic structures by Alleghanian deformation, however, leaves their original orientation open to question. Statistical geometry gives fairly consistent indications of Irish Mountain nappe movement a little to the west of north, and Lebanon Valley nappe movement a little to the east of north in this area. However, small scale structures may deviate considerably from these trends as a result either of original variability in the Taconic trends, differential Alleghanian reorientation, or both.

Minor late Alleghanian deformation is shown by scattered occurrences of late crenulation cleavage in argillaceous rocks and rare indications of the same event in the carbonate terrane. This deformation is inclined to the main Alleghanian trend but parallel to the margin of the Triassic basin. It is suggested in discussion of the Triassic structure that the north margin of the basin in this area may have been originally defined by a steep thrust of late Alleghanian age which would correlate with a known orogenic episode. The late Alleghanian deformation of the Lower Paleozoic rocks is at least consistent with such a fault.

Structural Levels

Paleozoic rocks of the Sinking Spring quadrangle are cut by a number of south dipping thrust faults. These thrusts produce a superposed pile of slices in which older rocks generally occupy higher structural position, though rocks in individual slices are not necessarily overturned, and may have different internal structure and stratigraphic affinities. Related components of the pile form structural levels which have been designated in their usual order of superposition at the surface in this area. Owing to different ages and inclinations of the thrusts producing the pile the order of superposition is not entirely consistent locally and varies more as traced away from the Sinking Spring quadrangle.

The major structural levels are obviously the major nappe units; the pelitic envelope, the Irish Mountain nappe, the lower limb of the Lebanon

Valley nappe approximately in its Taconic position, and the overriding Alleghanian thrust plates of the upper limb of the Lebanon Valley nappe. These have been designated structural levels A for the structurally lowest and stratigraphically youngest to D for the structurally highest and stratigraphically oldest. Magnitude of displacements associated with the nappe systems are the order of miles and probably tens of miles. It does not follow that discontinuities across thrusts separating nappe units are that large, but the displacement must be substantial. Actually superposition of carbonate rocks of structural level B on the nappe envelope, level A, is a relatively local anomaly. The Leinbachs thrust producing this relationship has one of the lesser displacements deduced for mapped major thrusts. Shales south of the Leinbachs thrust, however, are included in structural level B with Irish Mountain nappe carbonates by reason of superposition and structural behavior.

In a somewhat similar way structural rather than stratigraphic criteria are employed in selecting the appropriate designation for the lower slices of level C which apparently derived from the Irish Mountain nappe, level B. Those slices, however, are caught up in, significantly transported by, and bear a distinct tectonic impress of emplacement of the Lebanon Valley nappe.

The first order structural levels identified above are sliced into second order structural levels by substantial thrusts which can be traced beyond the quadrangle boundaries (Figure 23) and in some cases across several quadrangles (Tectonic Map, Plate 2). Within first order levels the second order levels are identified numerically in ascending order, e.g., B1, B2, B3. Estimates of minimum displacement between adjacent second order levels generally fall in the thousands of feet order of magnitude, but in many cases an order of magnitude higher—tens of thousands of feet or a few miles—may be more accurate. Structural contrasts between second order levels are appreciable in many instances, in part as the result of the variable tectonic response of different lithologies, and in part the result of differing structural history or position. The second order structural levels provide the principal basis for subdivision in the subsequent description.

Third order structural levels have been designated where it is more or less locally convenient to distinguish tectonic superposition of elements within or related to second order levels. This situation arises where thrusts split or include slices of appreciable size, or where second order levels include and truncate smaller thrust slices. Third order levels are designated by adding a lower case letter to the second order symbol.

The outcrop area of the structural levels appearing in the Sinking Spring quadrangle is shown in Figure 23 and on the Tectonic Map, Plate

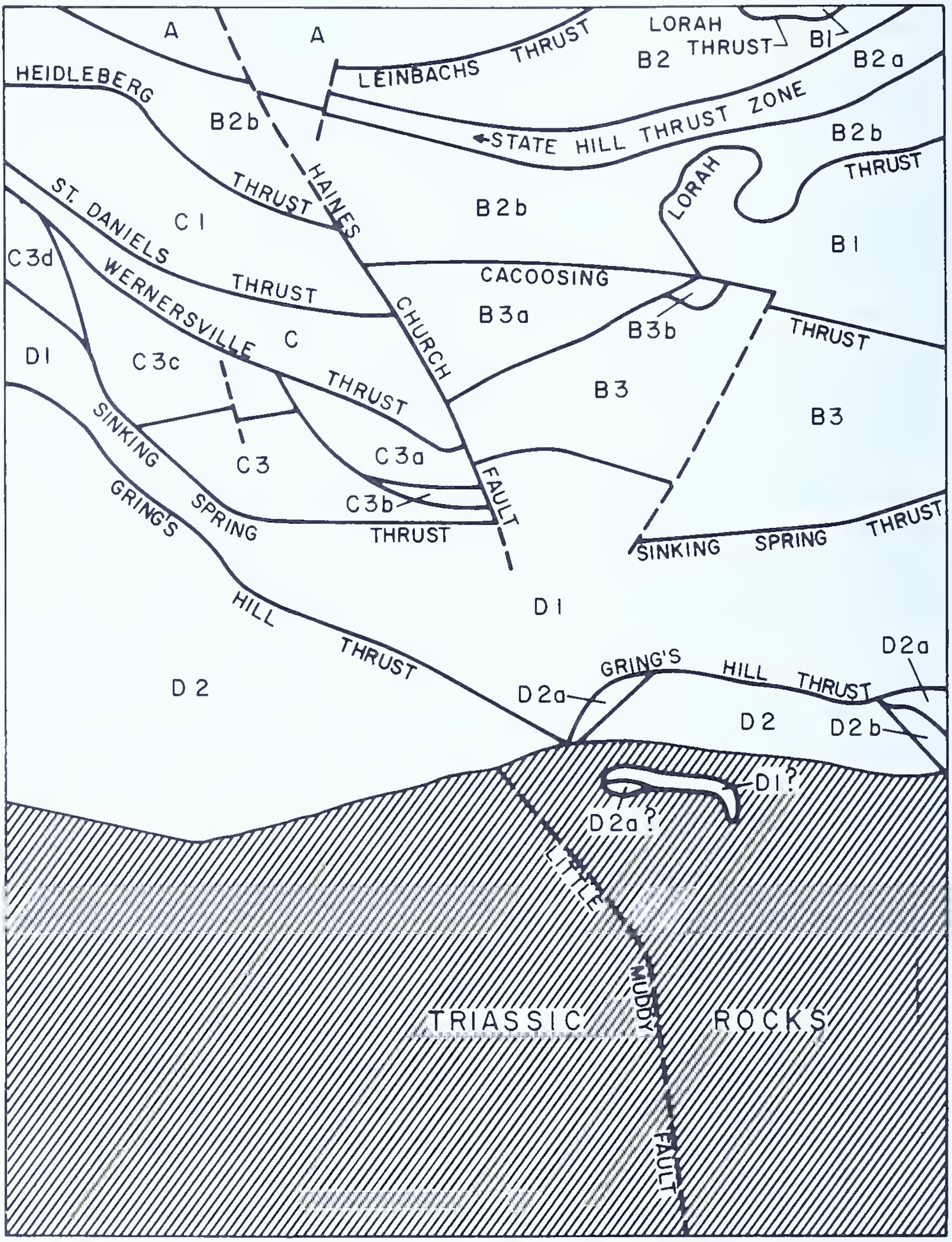

Figure 23. Structural levels in Sinking Spring quadrangle.

2. The latter also shows several additional levels not present or not exposed in the Sinking Spring quadrangle but found in adjacent areas, which are included to help place the Sinking Spring exposures in their regional setting.

Structural Elements

Structural elements comprise all the individual components, surfaces, folds, and lineations amenable to observation or measurement which collectively form the overall geologic structure. Some elements are penetrative (that is, statistically present in a random subsample) at some useful scale and their repetition defines a structural fabric. Such elements are called fabric elements, and analysis of their distributive geometry provides a basis for some structural inferences beyond those which may be obtained by direct observation.

Fabric Element Notation

For purposes of analysis, fabric elements have been given alpha-numeric designations. Certain conventions in notation are well established and are observed here. Practice has been more variable in other aspects. The notation employed here is believed to be consistent with most recent practice and has been selected as reasonably simple and internally consistent. Designations actually employed are given in Table 1. The principle of the notation scheme is systematic and allows for possibilities not actually employed in the analysis.

Table 1. *Fabric Element Notation*

D_1	First stage deformation, also used collectively for fabric elements or fabric generated by first stage deformation.
D_2	Second stage deformation.
D_3	Third stage deformation.
B_1	Fold axis of first stage deformation.
B_1'	Cross fold axis of first stage deformation.
B_2	Fold axis of second stage deformation.
B_2^1	Fold axis of second stage deformation developed in S_1 rather than S_0 as otherwise implied.
B_2'	Cross fold axis of second stage deformation.
B_3	Fold axis of third stage deformation.
B_3^1	Fold axis of third stage deformation of S_1.
S_o	Bedding or lamination.
S_1	Flow cleavage developed in D_1.
S_2	Fracture, slip, or crenulation cleavage developed in D_2.
S_3	Crenulation cleavage developed in D_3.
La_1	Any lineation approximately aligned with and genetically related to the *a* fabric axis of D_1.
La_2	Any lineation approximately aligned with and genetically related to the *a* fabric axis of D_2.
L_{b1}	Any lineation aligned with and related to B_1.
L_{b2}	Any lineation aligned with and related to B_2.
L_{b3}	Any lineation aligned with and related to B_3.
L_{ox1} L_{ox2} L_{ox3} L_{1x2} L_{1x3}	Intersections of S surfaces of same numbers used to identify lineations where the generating planes are of particular significance. Where the lineation has the same geometric orientation as a fold axis, it is commonly designated L_b.

Direct observation provides evidence of several stages of deformation which can be sequentially ordered by their interrelations in favorable circumstances. These have been designated D_1, D_2, and D_3. The symbol is used as a shorthand notation for the processes or results collectively of a given deformational stage.

Fabric elements comprise surfaces designated by S and linear elements designated by L. Bedding is an original surface of the fabric designated S_0 (which may be read either S zero or S“$_o$” implying original). All other surfaces are the product of deformation and are identified by a subscript which corresponds to the generative stage of deformation as S_1, S_2, and S_3.

Fold axes are not usually penetrative at the scale of observation, but they are an element which is a cardinal reference in fabric analysis. They are conventionally designated B (or a typographic variant thereof) with subscripts here employed corresponding to the generative deformation. Fold description in stratified rocks is commonly presumed to refer to folds in bedding (S_0); but, in some cases, the fold is measured in another surface, specifically flow cleavage (S_1) in this report. In this case the superscript 1 is added to identify the reference surface, as in B_2^1 and B_3^1. Cross-fold nomenclature derives from Sander (1930) but pertains only to his case of syngenetic cross folds, $B \perp B'$. Sander's case, $B \wedge B'$, of sequential cross folds is implicit in the recognition of fold generations which could be expressed in the style of Sander as $B_1 \wedge B_2$.

The term lineation is used here in the general sense of Cloos (1946, p. 1) to include all linear structures regardless of origin and scale. Certain lineations are of particular interest for structural interpretation, however, because on an empirical or theoretical basis they approximate the direction the fold axes of a given stage of deformation and others lie in the plane normal to the axes and reflect componential movement. Such lineations are important elements of the structural fabric and have been collectively designated by reference to the appropriate fabric axis as La_1, La_2, Lb_1, etc., regardless of the particular type of structure represented. The use of this notation or the equivalent terms lineation in *a* and lineation in *b* used by Cloos (1946), is fairly widely understood, though it is not endorsed by some recent authors on the theory of structural analysis (Turner and Weiss, 1963; Ramsay, 1967) because it is open to theoretical objections which assume very practical consequences in the analysis of more complex, significantly metamorphosed terranes. There do not seem to be suitable alternative collective terms, however, and the kinematic implications of the designation are at least approximately valid for the structures under consideration.

Lineations may be produced by the intersection of surfaces. In some cases, notably the intersection of bedding and cleavage, this lineation has a well-known relation to the fold axis and is ordinarily designated as Lb_1 here. Certain other intersection lineations, however, are indirectly related or generally inclined to the usual reference axes. Such lineations are best defined by the surfaces producing them and are designated by the subscripts of the intersecting planes separated by an "x" (indicating the crossing) as in L_{2x3}. The same method of notation may be applied to lineations having an axial orientation and will be used when the intersection property is germane to the point in consideration. Thus, the bedding (S_0) cleavage (S_1) intersection is usually designated Lb_1, but it may be noted L_{ox1} when its origin by this intersection is of particular significance.

Bedding (S_o)

Bedding is the most prominant surface in most of the section and provides the usual, presumably initially horizontal, datum for description and analysis of subsequent deformation. Throughout much of the section it is a structurally active surface and locus of movement, but it has been transposed passively in the more homogeneous rocks. Evidence of primary stratification is often obscure or obliterated in the more argillaceous rocks of this area (Figure 25). In these rocks the conspicuous parallel structure is a slaty cleavage which is normally axial to folds in bedding where it can be observed. In many cases, the relation of cleavage to bedding cannot be established, and observable deformational structures are those affecting the cleavage. With respect to these rocks, therefore, bedding cannot be presumed to be the principal datum of structural reference.

As a structural element the bedding assumes most significance where beds vary in competence, that is in rheologic properties, and exercises strong control on deformation. This relationship undoubtedly applies where graywackes are interbedded with the shales, though exisiting exposures provide no notable examples. Interbedding of limestone and dolomite in varying proportions is characteristic of most of the thick Upper Cambrian and Lower Ordovician carbonate section and exercises a strong control on observed structures. Other less conspicuous competence variations in the limestones, which are often correlated with obvious differences in lithologic details, influence local structural variations; but the dolomite beds seem to be the competent struts which control the general scale of buckling.

General bedding characteristics of the individual stratigraphic units are given in the formational descriptions. One feature common to all the heavy bedded carbonate units, which was implicitly described as a depositional property, merits notice. Distinct bedding units in these rocks are commonly on the order of 2-feet thick and rarely exceed 4 feet. They are typically delimited by pronounced thin partings which have concentrations of insoluble material sometimes showing clear impress of interstratal slip. The majority of partings separate clearly distinct depositional units characterized by at least minor differences in lithology. Sometimes there is no lithologic difference between adjacent beds as defined by the distinct partings; and, except for the parting, a series of beds appears as a depositional entity. While the partings may represent quasi-periodic transient disturbances of low frequency in an otherwise long persistent depositional environment, an alternative possibility is that the interval of constant lithology is, in fact, a single depositional unit, and the partings are flexural slip surfaces of tectonic origin. The question is not easily resolved, but it poses no real problem in structural analysis. Surfaces of flexural slip have the same geometric signficance whether or not they are original planes of stratification.

Flow Cleavage (S_1)

Cleavage terminology is at present unsatisfactory because it is an inconsistently applied mixture of genetic terms of questionable accuracy, descriptive terms, and descriptive terms extended by reason of apparent genetic similarity to situations of which they are not properly descriptive. The term flow cleavage is employed here to encompass all cleavage which is demonstrably associated with rock flow without implying the correctness of any of the particular mechanisms educed to explain it, which are still in dispute. Recent authors (Dennis, 1967; Ramsay, 1967; Turner and Weiss, 1963) recognize this term as equivalent to slaty cleavage and schistosity, which they prefer; but both of these have lithologic referents which do not display the cleavage style developed in well stratified rocks of varying competence.

True slaty cleavage is well developed in shale and argillaceous limestone throughout the area. It is represented by a parting or incipient parting continuously divisible down to the scale of the constituent grains. It is parallel to axial planes of folds in bedding in most cases where these can be distinguished (Figure 24) and shows little tendency to fanning. In a large portion of the rocks with slaty cleavage, bedding has been obliterated. Original lithic discontinuities in many of these rocks were probably so subtle that only minor movement and recrystallization was sufficient to

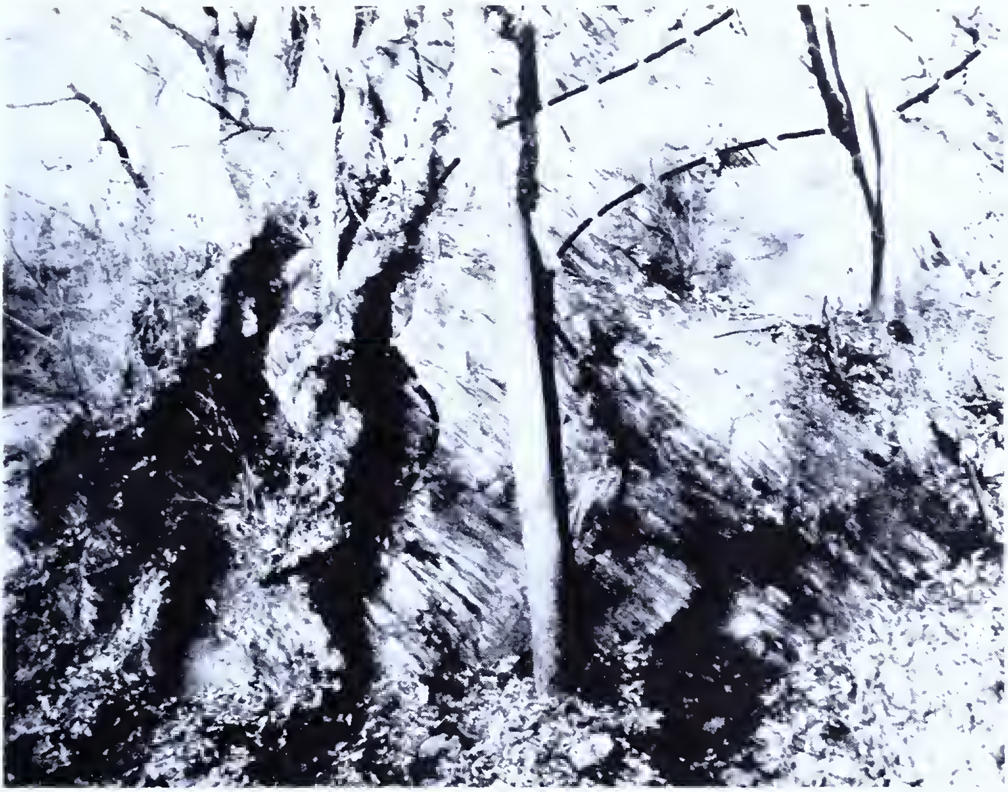

Figure 24. Well-developed slaty cleavage (S_1) in the Hamburg Sequence near Rebers Bridge. An obscure bedding trace is visible in this exposure and is emphasized by dashed lines. Folds are kinematically congruent with the cleavage and are B_1.

effect this obliteration, but quite substantial movements along the cleavage are indicated by disruption and reorientation of competent layers in some cases (Figure 25).

In limestones of the area, partings on flow cleavage are much less prominently developed than in the shale. Even where noted as well developed, partings are frequently of the order of 1 to 3 cm spacing, as in Figure 26. Incipient parting, or at least a fabric grain in the cleavage direction, is much more common as shown by cleavage intersection lineations in rocks which show no obvious tendency for a cleavage parting. Mineral fabrics have not been systematically investigated, but the example shown in Figure 27 shows substantial preferred orientation of grain boundaries parallel to the axial planes of the microfolds in the normal position for megascopic cleavage S_1. With different mineralogy it seems quite likely that a strong parting would be associated with this fabric, but this rock shows only a weak tendency for preferential breakage in this direction.

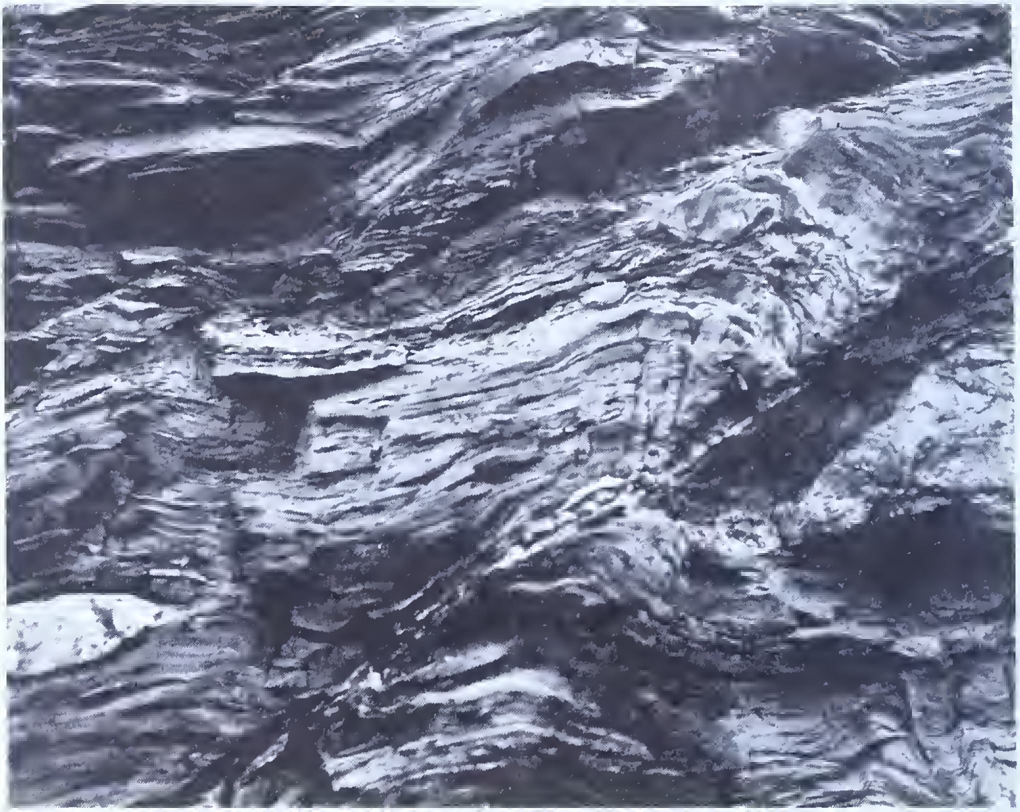

Figure 25. Widely separated lenticular boudins of thin conglomerate bed of Hershey Formation oriented in flow cleavage (S_1).

Cleavage fanning around fold hinges in the limestone is sometimes evident in outcrop, and is even more apparent in stereograms of individual folds. Cleavage may also be refracted when transecting beds of differing competence (Figure 28). Though less conspicuous in limestone than in many terrigenous clastic sequences, it is a common phenomenon that in the more competent beds, where cleavage is most refracted from its statistical approximation of the axial plane of the associated fold, it is also more coarsely developed. This coarse refracted cleavage is sometimes separately distinguished from flow cleavage as "fracture cleavage," though their common genesis can often be demonstrated, as in the illustrated case, where changes in orientation and aspect are gradational. The term fracture cleavage in this report does not refer to such rheologically controlled variations of the flow cleavage; rather it is applied to a clearly distinct surface (S_2) more closely related to jointing. The combined effects of cleavage refraction and fanning may produce an appreciable spread of cleavage orientation which is approximately coaxial with the fold, though no rotation of cleavage surfaces is necessarily implied.

Dolomites in the area, as distinct from limestones, rarely show any appreciable cleavage. This relationship is well displayed in illustrations showing interbedded limestones and dolomites, notably Figures 26 and 34. The absence of cleavage development is a consequence of the different rheologic properties (competence) of the dolomite with pronounced effects on the form of folds and orientation of movements. A thin section of a presumably representative dolomite (Figure 29) shows an absence of grain orientation in contrast to the limestone section of Figure 27. The difference in structural development thus extends to the microscopic fabric.

A special case of cleavage development is parallel to stratification in favorably oriented and located limestone beds; and it seems more directly related to the simple shear of the major thrusting than the associated folding. It is associated with strong development of lineations in the *a* direction on bedding surfaces, but it is not always present in such cases. Observations of stratification with strong *a* lineation are concentrated in, but not limited to, the vicinity of known thrust faults. The cleavage of

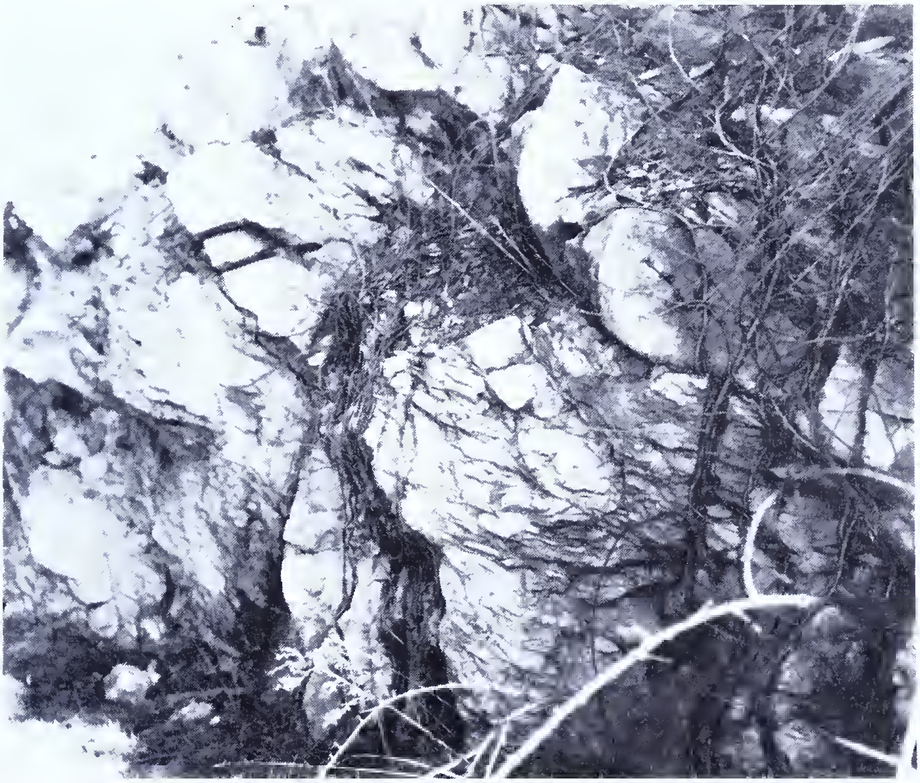

Figure 26. Good flow cleavage (S_1) development in limestone of Richland Formation. Note very poor cleavage development and boudinage in interbedded dolomites.

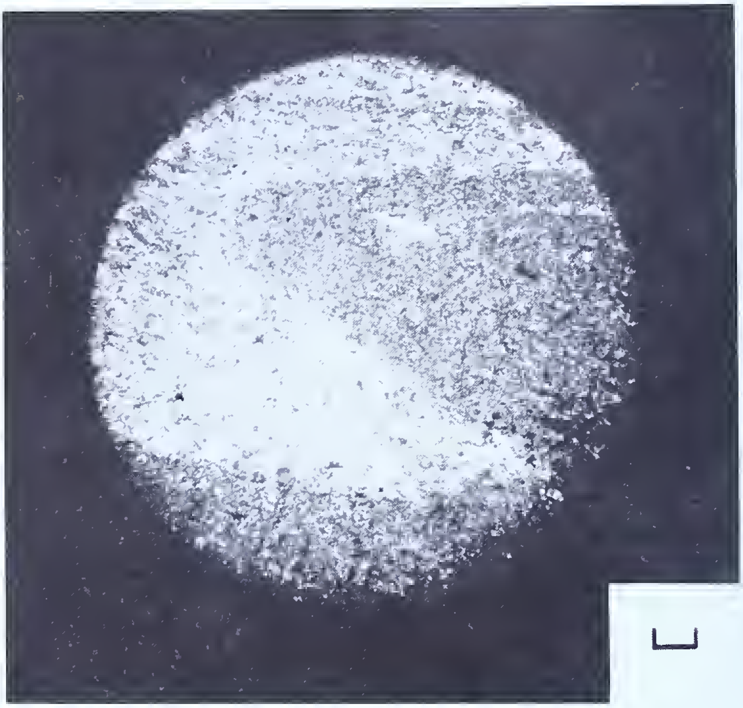

Figure 27. Photomicrograph, recumbent folds and grain orientation in laminae of Epler Formation. Section is cut normal to fold axes and parallel to strong "a" lineation on bedding surface. Only short limb is shown, complete fold pairs are widely separated. Crystal fabric shows distinct preferred orientation of moderately elongate calcite grains parallel to axial surface. (Scale length 200 microns. Field is about 1/12-inch wide).

this type probably has a similar distribution, but definite observations are too sparse for independent generalization. Megascopically this cleavage is characterized by spaced, distinctly phyllitic partings, commonly strongly lineated. In thin section (Figures 30 and 31) it is evident that these partings are tectonic surfaces rather than simply depositional shale seams, though they parallel stratification. The origin of this cleavage is evidently slip distributed through the body of the affected beds where the general pattern of movement is interstratal slip controlled by rheologic contrasts between beds. The local pattern of movement is that encountered in flexural-slip folding, but it would appear the required magnitudes are of a larger order. This conclusion follows from the observation that this style of parting is not generally associated with the limbs of folds in which flexural slip was a significant deformational mode; rather it has a restricted range of southerly dips evidently more related to the gross movement pattern than local movements in fold limbs.

The examples of rocks with distinct preferred orientation of mineral grains illustrated here (Figures 27 and 31) come from the lower limb of the Lebanon Valley nappe. Microfabrics have not been systematically investigated, but there are some indications that Lehigh Valley sequence rocks are generally not so affected. This would be an aspect of difference in structural facies.

Shale outcrops sometimes give an indefinite to distinct impression that there may well be a locally pervasive compositional lamination fully transposed into the foliation plane. In this case the compositional layering is probably controlled by the cleavage, rather than the opposite, as noted in the previously described limestone. Such transpositions are perfectly ordinary in strongly folded reasonably homogeneous rocks of low competence and have no necessary relation to thrusting. On the other hand, there is nothing in the data evaluated which precludes the possibility that observations of favorably oriented foliation in the shales with a strong La_1 might be directly related to thrust slip. There is no clear geometric distinction in any of these cases. The lineated, layer-parallel cleavage falls within the normal range of cleavage dips; and, as the

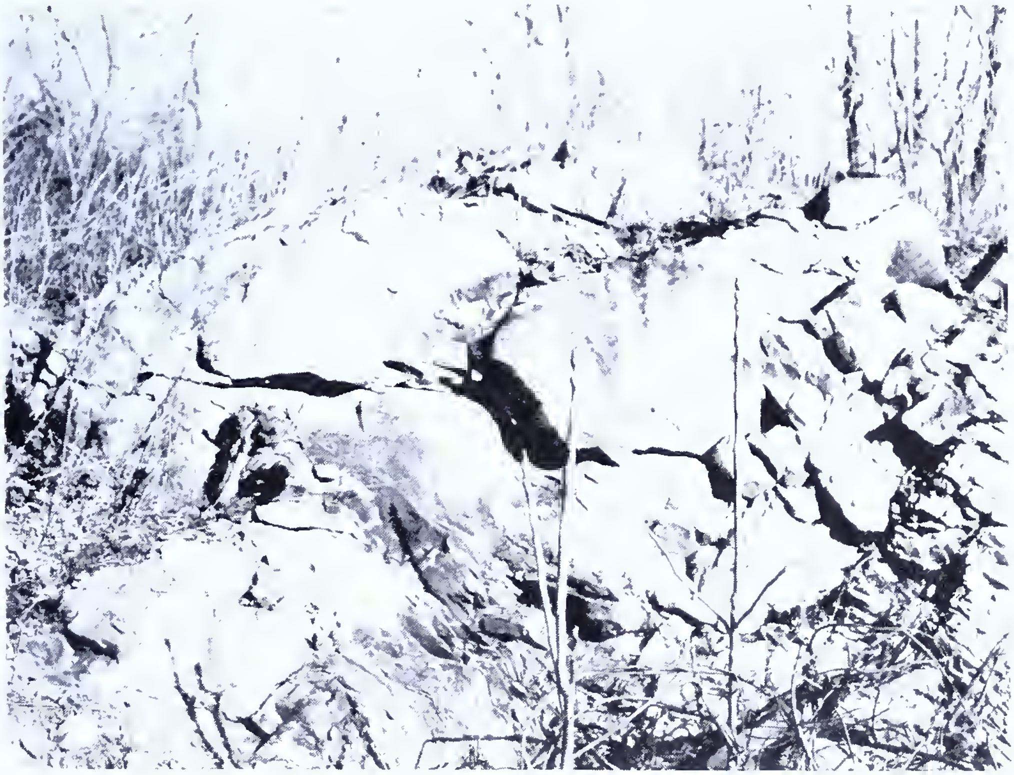

Figure 28. Refraction of flow cleavage in Richland Formation. Note differing cleavage development in the various beds.

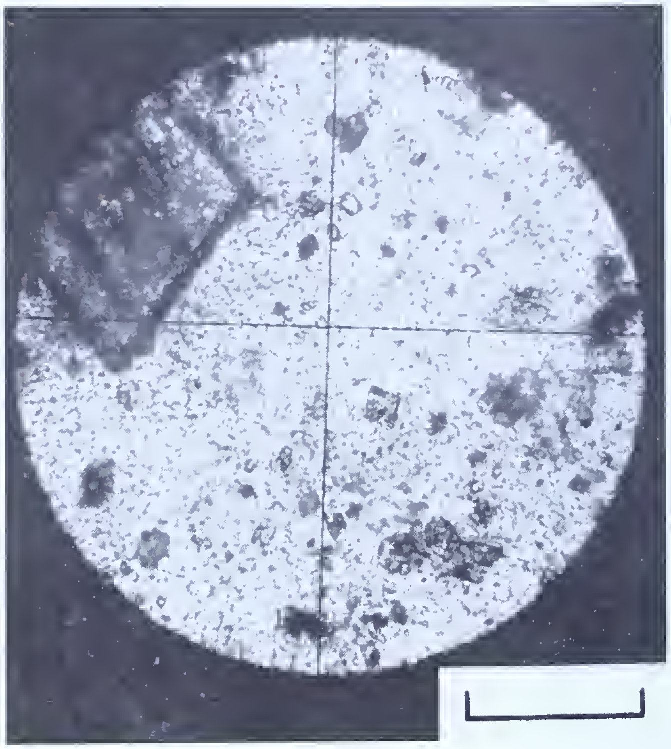

Figure 29. Photomicrograph from thin section of typical dolomite in Ontelaunee Formation. Scattered rhombs of dolomite in a very finely crystalline matrix of dolomite and calcite with irregular grain boundaries. There is no evidence of preferred shape orientation in contrast to the limestone in Figure 27. Matrix apparently has a recrystallization texture which indicates possibility of preferred crystallographic orientation if recrystallized in a stress field, but the grains are too small for investigation by conventional petrofabric methods. (Scale length 200 microns. Width of field is somewhat less than 1/32 of an inch).

thrusts and folds are directly related, fabric of both have at least a common *b* axis.

Throughout the area, flow cleavage typically dips about 5 to 50 degrees south or southeastward, depending largely on the degree of assymetry or overturning of the associated folds. There is considerable variation that is evidently the impress of subsequent deformation. With one exception, the flow cleavage is everywhere genetically related to the oldest recognizable deformation (D_1) and is accordingly designated S_1. The exceptional case involves indications of prelithification (?) deformation in the State Hill thrust zone where folds older than, and geometrically and dynamically unrelated to, the local cleavage appear to antedate it.

Later Cleavages (S_2 and S_3)

Cleavage inclined to and obviously younger than S_1 has been observed in both carbonates and shales in a number of places throughout the area. The cleavage may be variously characterized as fracture, slip, and crenulation cleavage, if these terms are taken in descriptive sense without genetic implications. Lithology of the enclosing rock seems to be the principal controlling factor in the style developed.

In the argillaceous rocks, sometimes including argillaceous partings in the heavy-bedded carbonates, the intersection of the fracture cleavage with older surfaces, both S_0 and S_1, is frequently marked by minute folds or crenulations which may be spaced 20 or more to the inch in some zones and more widely spaced or absent in other parts of the same exposure (Figure 32). In some areas two such sets of crenulations are superimposed and provide the basis for separating two generations of crenulation cleavage S_2 and S_3. The later, S_3, is quite uniformly steep southerly to occasionally steep northerly dipping. S_2 in the shales is more variable in dip but maintains a relatively constant strike. No strong tendency to preferential parting along the crenulation planes was noted in most instances, and field recognition of S_2 in shale was largely controlled by the presence of crenulations. Cleavage fragments in the Martinsburg regolith sometimes show a distinct secondary grain defined by a faint lineation on S_1 and parallel boundaries oblique to the S_1 faces. In many cases this structure may be an S_0 trace, but it has been observed on fragments with distinct compositional laminae inclined to S_1 and another indistinct plane and lineation, presumably in this case S_2 and L_{1x2}. Such fragments indicate the presence of crenulation is not a necessary consequence of S_2 development, but if partings on this surface were present in uncrenulated shale they were not ordinarily distinguished from joints.

Pencil slates formed by about equally developed intersecting cleavage partings are locally encountered, especially near the trace of the Hains Church fault. This represents a special case of late cleavage which seems to have no systematic relation to more pervasive structures. Alterman (personal communication) reports that in her mapping of a nearby area she finds the pencil slate zones useful as a criterion for fault tracing. The pencil slates seem to have the same significance in this area. Exposures are predictably poor in these intensely cleaved areas, and no evidence bearing on the relative age of these and other late structures was discovered.

Second generation cleavage in the Hershey Formation is probably present through much of the area by indications in float and inferior exposures, but was measured only in the railway cut north of the Wer-

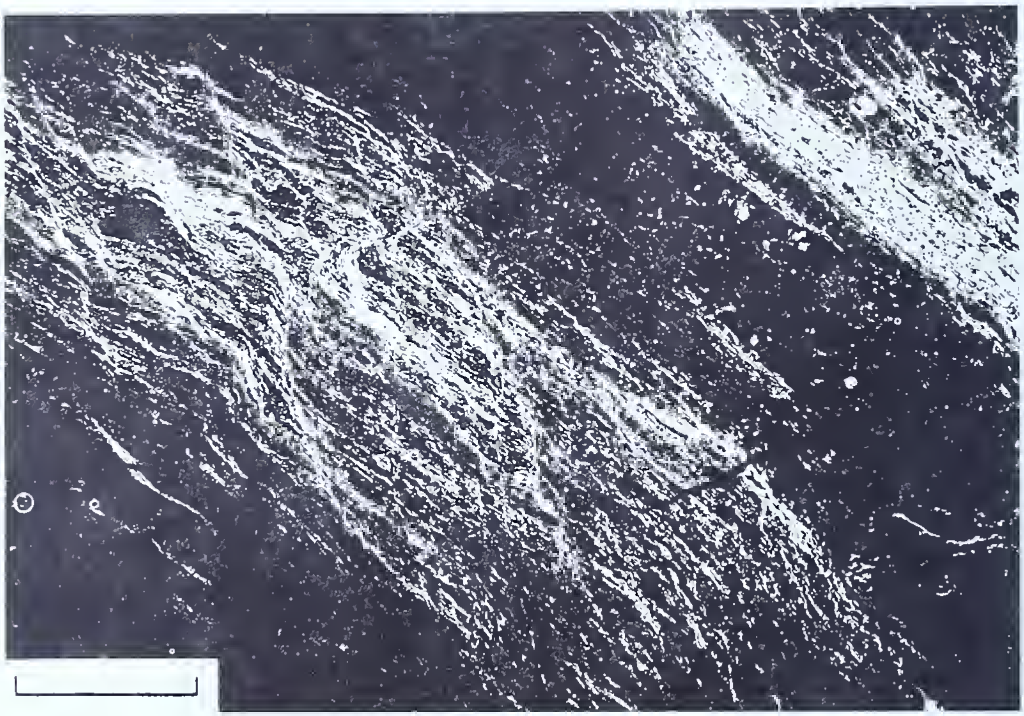

Figure 30. Enlarged (negative) image of thin section showing intensely cleaved zones parallel to stratification in limestone of Epler Formation. Cleaved zones may have been localized by compositional laminae though they lack silty insoluble concentrations commonly observed in noncarbonate-rich Epler laminae. Present foliation defined by recrystallized sericite (light lines in this negative image, dark in Figure 31) are of tectonic origin and clearly transect original grains in the zones of less intense development. Section is cut normal to foliation and approximately parallel to strong "a" lineation on parting; dip in the figure approximates field attitude. Steeply inclined crenulation cleavage may be an incipient development of S_2 in a syle which is common in the shaly rocks of the area but was not noted as a megascopic feature of the limestones. (Scale length 0.5 centimeters).

nersville State Hospital where structural relations are clear and well exposed (Figure 33). Development is intermediate in character between the shales and the heavy-bedded carbonates. It is best charactrized as a slip cleavage composed of closely spaced fractures showing some displacement. It differs from the shale crenulation cleavage somewhat in scale and in not having a regularly alternating orientation of the antecedent surfaces in interfolial domains. In this area, at least, the S_2 attitudes are fairly uniform, dipping southeastward and the rotation axis

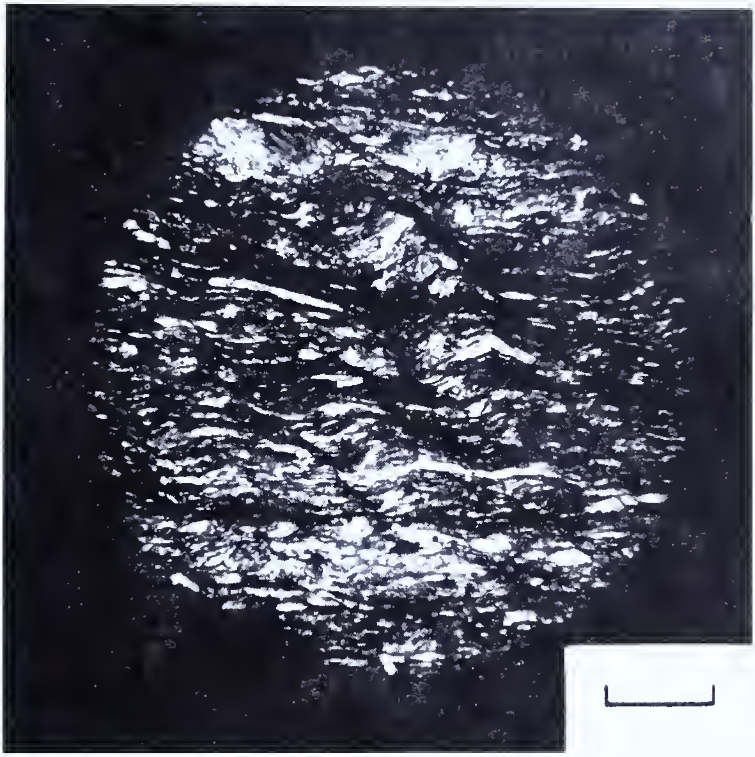

Figure 31. Photomicrograph, detail of Figure 30, showing strong preferred dimensional orientation of grains and bending and disruption by crenulation cleavage. (Scale length 200 microns. Field width is about 1/16 of an inch).

of the associated folds is in good agreement with D_2 axes deduced elsewhere.

Fracture cleavage consisting essentially of closely spaced, regular joints was noted in a number of carbonate exposures. It does not differ appreciably in character or orientation between limestone and dolomite and shows no indication of refraction. Owing to intense jointing of dolomite, fracture cleavage was not usually distinguished as such in dolomite exposures but was sometimes noted as an extension of fracture cleavage in limestone beds. The distinction between fracture cleavage and other planar jointing rests on the subjective decision that the fractures are effectively penetrative at the outcrop scale; that is, that they are ordinarily in any randomly selected small part of the exposure, or at least substantial domains thereof. In some case the fracture cleavage merges toward slip cleavage by the presence of minor displacements along it; but the development is less pronounced than the example of Figure 33 and lacks obvious associated folds. In marginal cases there is probably a tendency to identify a strong joint set as fracture cleavage if it shows indications of such slip. Slip on fracture cleavage and jointing was most commonly noted in laminated limestones. This fact, however, probably reflects ease in observation, rather than lithologically controlled development. The distributions of fracture cleavage orientations in the carbonates and crenulation cleavage (S_2) in the shales is copolar and quite similar. The clear implication is that the differences in style reflect differences in lithology only. This conclusion is reinforced by occasional observations of typical crenulation cleavage lineation on shale bands in carbonate formations and the incipient crenulation cleavage shown in Figure 30.

S_3 has always been identified as a crenulation cleavage if the rather coarse crenulation shown in Figure 34 be allowed this designation. In

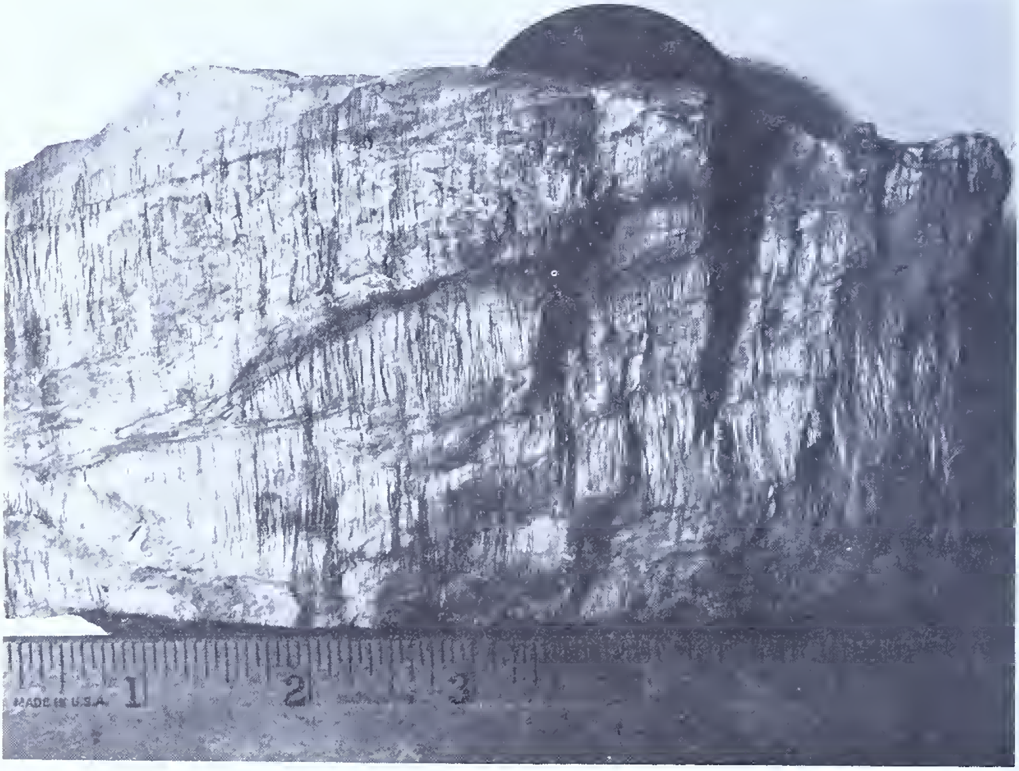

Figure 32. Crenulation cleavage (S_2) in lithic type 2 shale, Hamburg Sequence. Vertical lineation (L_{1x2}) is intersection of S_2 with flow cleavage (S_1) which lies in the plane of the photograph. Coarser lineation sloping down to left is the trace of the bedding intersection (L_{ox1}). An occasional faint lineation sloping somewhat more steeply to the right is apparently the trace of an incipient S_3 (L_{1x3}) which is evident in the strong oblique lighting of this photograph but was not noted at the field locality of the specimen. S_3 where recorded is commonly about as strongly developed as S_2.

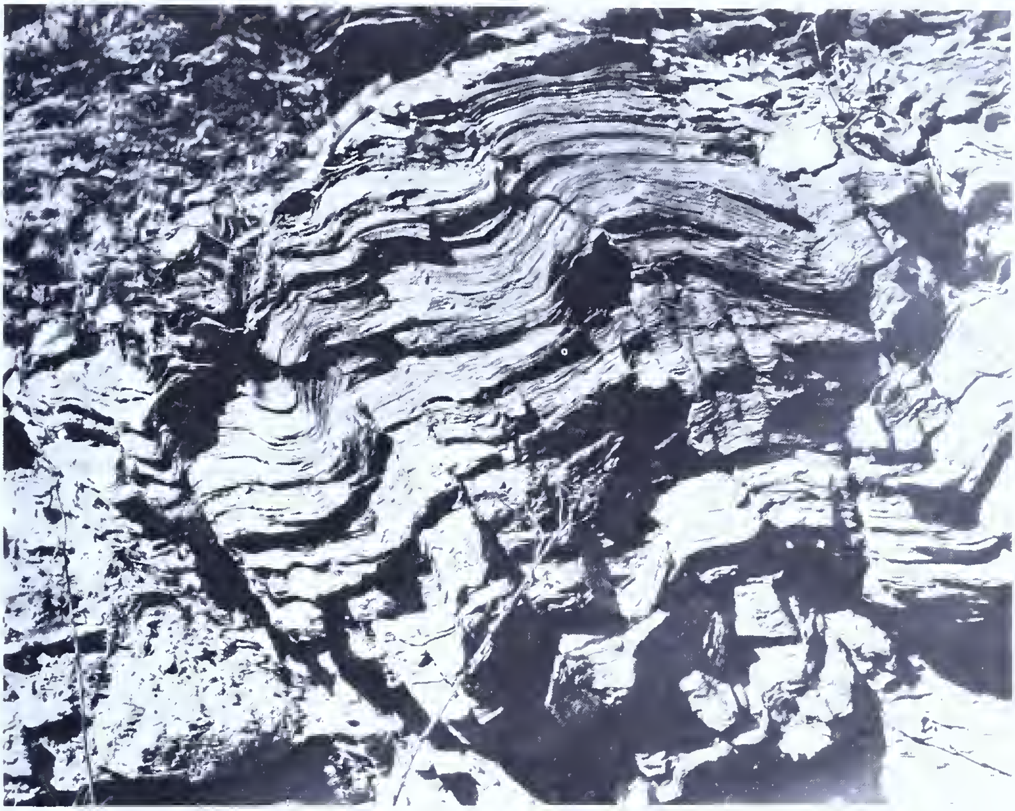

Figure 33. Slip cleavage (S_2) and associated minor folds ($B_2{}^1$) in flow cleavage (S_1) in Hershey Formation. Axis of recumbent fold in bedding can be indistinctly traced across lower part of photograph.

the shales it is distinguished from S_2 only by its uniform orientation and distinctive strike. The example illustrated in Figure 34 is the only one known in a carbonate formation, and then in an argillaceous bed. S_2 and S_3 are both present in this exposure, but direct observation of an intersection providing evidence of relative age was not possible. The attitude of S_3 in this exposure is identical to that in the shales to the north. S_3 orientation does not correspond to any significant concentration of joint attitudes recorded in Figure 36. Unlike S_2, there seems to be no relation between this surface and jointing.

Joints

The rocks of this area are abundantly fractured. It is rare to find a separation between fractures of as much as two feet and the spacing is more commonly measured in inches. A large majority of the fractures are healed with calcite or more rarely quartz seams and do not detract substantially from the present strength of the rock. In excavation it is

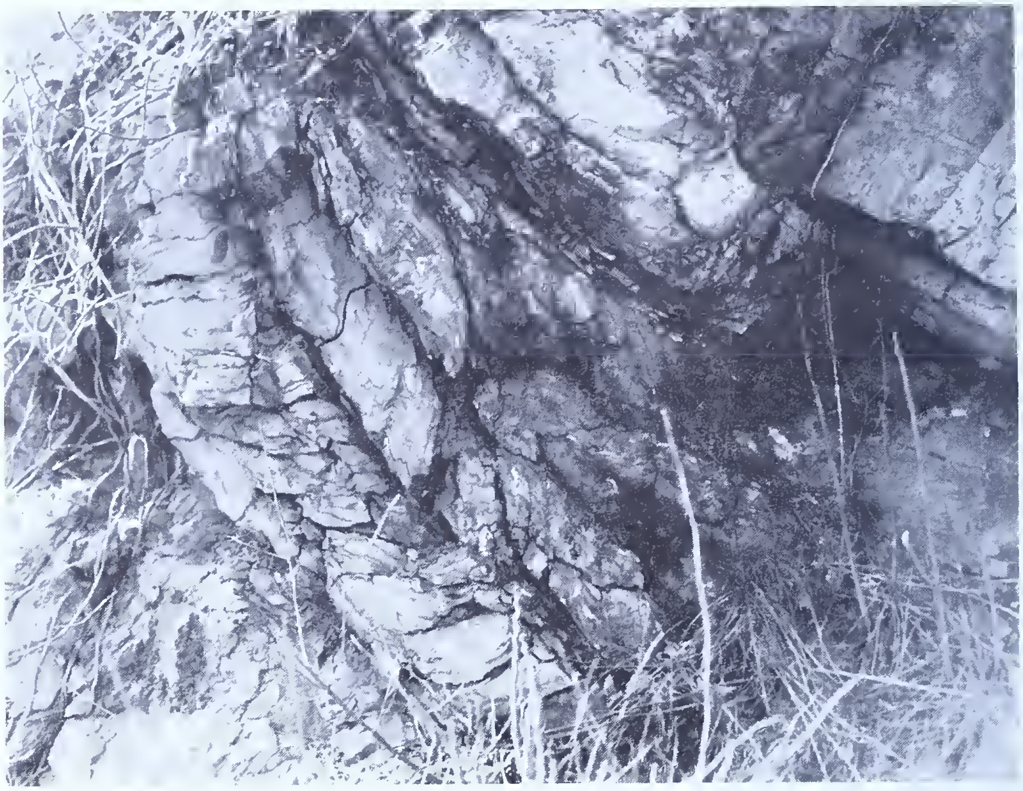

Figure 34. Fracture cleavage (S_3) and associated minor folds (B_3) in shaly layer of Richland Formation. Folds are visible both in compositional laminae (S_0) and flow cleavage (S_1). Trace of fracture cleavage (S_2) is most clearly marked by lineation declined to left on joint face at upper right of picture.

common for the rocks to part preferentially along these joints; but larger fragments frequently contain joints which have not parted, and, in some cases, the breakage is clearly across the joints.

In the argillaceous rocks the joint pattern is often quite complex, and the relationship to bedding is obscure (Figure 35). Where more massive beds are present, jointing tends to be somewhat more widely spaced and normal to the bedding. Attitudes of joints in shales may be more variable in the same exposure. Quartz veins are relatively more abundant in joints of the argillites than in the carbonates; and, in some areas, vein quartz makes a noticeable constituent of the shale float, though the veins are rarely conspicuous in outcrop.

Joints in the carbonate rocks are evident and their typical development illustrated in every carbonate exposure photograph of this report. They are typically steeply inclined or normal to bedding and are more prominent and closely spaced in magnesian than calcareous rocks. This property is an indication of the greater brittleness of the dolomites which is also reflected in other aspects of their deformation. On weathered surfaces there is often selective solution along the joint planes in dolomite, even where the joints are fully healed and the rock quite coherent. This solution effect produces "slash weathering" or "elephant hide" texture which is often a useful field criterion for identification of dolomite in this area.

Carbonate exposures represent a minute portion of their total subcrop area; and in many cases the fact of outcrop itself is sufficient to suggest that the exposed rock is somewhat atypical. The larger exposures in quarries and cuts indicate that larger fractures, probably minor faults in some instances, commonly with some solution development or unusually deep weathering, are present at spacings in the order of 50 to several hundred feet. Such master joints are very obscure, as they commonly are represented by covered intervals even in large exposures; but they apparently form a significant feature of the geologic fabric. Their presence is indicated on air photographs, wherever soil conditions are favorable, as linear elements not parallel to the lithic strike. They may also

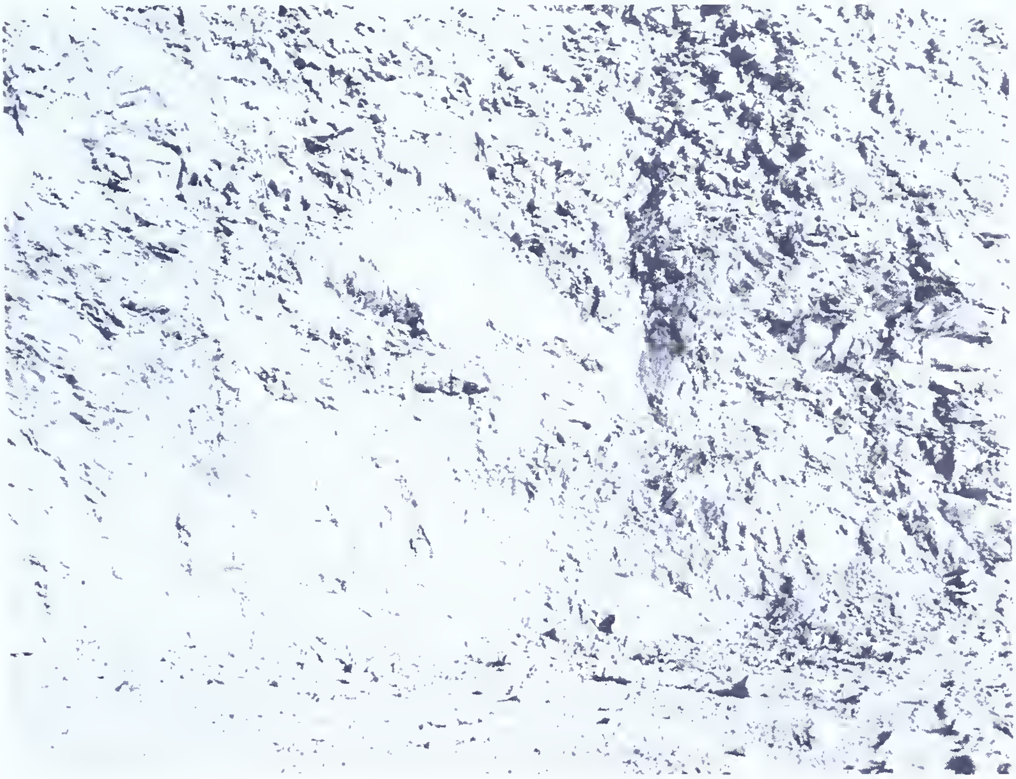

Figure 35. Jointing in Hamburg Sequence, Glen Gary Shale Brick Company quarry southeast of State Hill. Shovel teeth marks provide an indication of scale.

represent a factor in producing strike-parallel lineations. The master joints seem to exert some influence on minor topographic features, stream alignments, and dike traces.

Joint orientation data was less systematically collected than measurements on other structural elements. The available readings are summarized in Figure 36. Despite the impression that shale joints appear more variable in a single exposure than they do in the carbonates, data for the whole area plotted separately for shale and carbonate show the same distribution, and lithology does not seem to be a significant control in statistical orientation. The number of observations is relatively small, but the consistent pattern obtained in rheologically distinct rocks and from well separated exposures suggests that the illustrated distribution is an adequate approximation of the real geometry.

The highest concentration of poles represents joints dipping steeply west-northwest, which indicates they are roughly parallel to the average strike of the bedding and steeply inclined to it. The distribution of this cluster is clearly along a girdle that is consistent with the regional fold trends and more particularly, the main Alleghanian D_2. Other concentrations of joint poles may have less obvious mechanical relations to other structural elements which will be suggested in analysis of the deformation.

Thrust Faults

Segmentation of the area into structural levels by major thrust faults has already been discussed. These major thrusts invariably occur in areas of extremely poor exposure, and their presence is largely deduced from stratigraphic and structural discontinuities. In many cases exposures near the thrust trace show substantial impress of the thrust movement in the form of strong development of lineations in *a* and B′ folds, which are discussed in subsequent sections. With the exception of the Lorah thrust, which is clearly folded, these thrusts have been treated as approximately planar elements in construction of the cross-sections of Plate 1, as there is no clear evidence of folding in their map pattern and very little subsurface control. This interpretation clearly represents a simplified approximation, as a few wells provide some evidence of structural relief even on the youngest thrusts. The dip of the major thrusts is deduced to be generally at a moderate to low angle southward from their map pattern and in conformity with the majority of minor thrusts observed in outcrop. There is some variation in deduced attitude, however, which may reflect differences in both original attitude and subsequent warping.

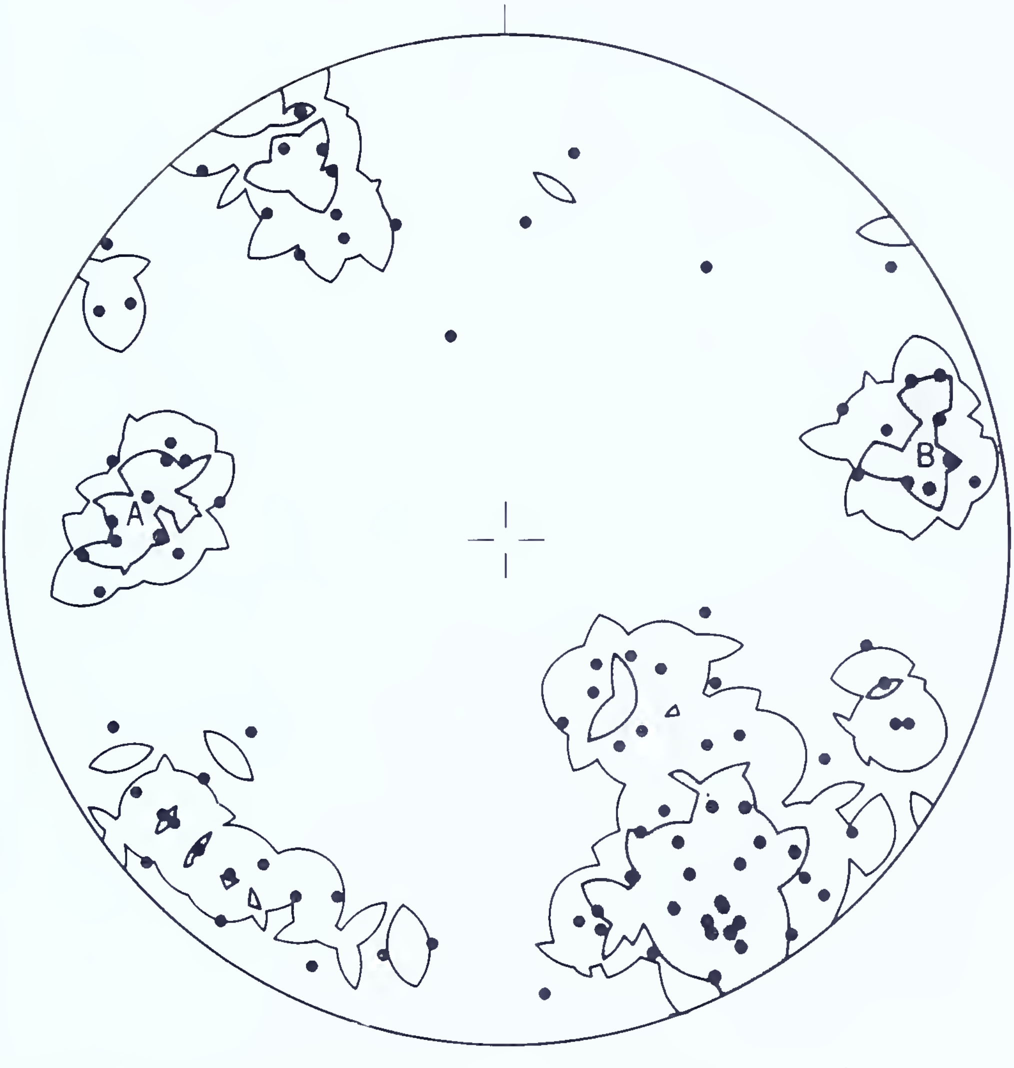

Figure 36. Joint orientations measured in Sinking Spring quadrangle. Contours at 2 to 4 percent with 8 percent point maximum. Letters on diagram refer to discussion in subsequent sections of the text.

The displacements on the major thrust have been estimated through several orders of magnitude ranging from a number of miles to at least a few thousand feet. A number of exposures show minor thrusts which complete the spectrum down to surfaces which can be traced for only a few inches and offset laminae in a single bed a fraction of an inch. Most of the conspicuous minor thrusts (Figures 37 and 38) visible in outcrop have displacements larger than the scale of the exposure, which must be estimated in tens of feet minimum and may well be appreciably more. Such thrusts, though common, cannot be traced between outcrops and are consequently not mappable. The single exception to this generaliza-

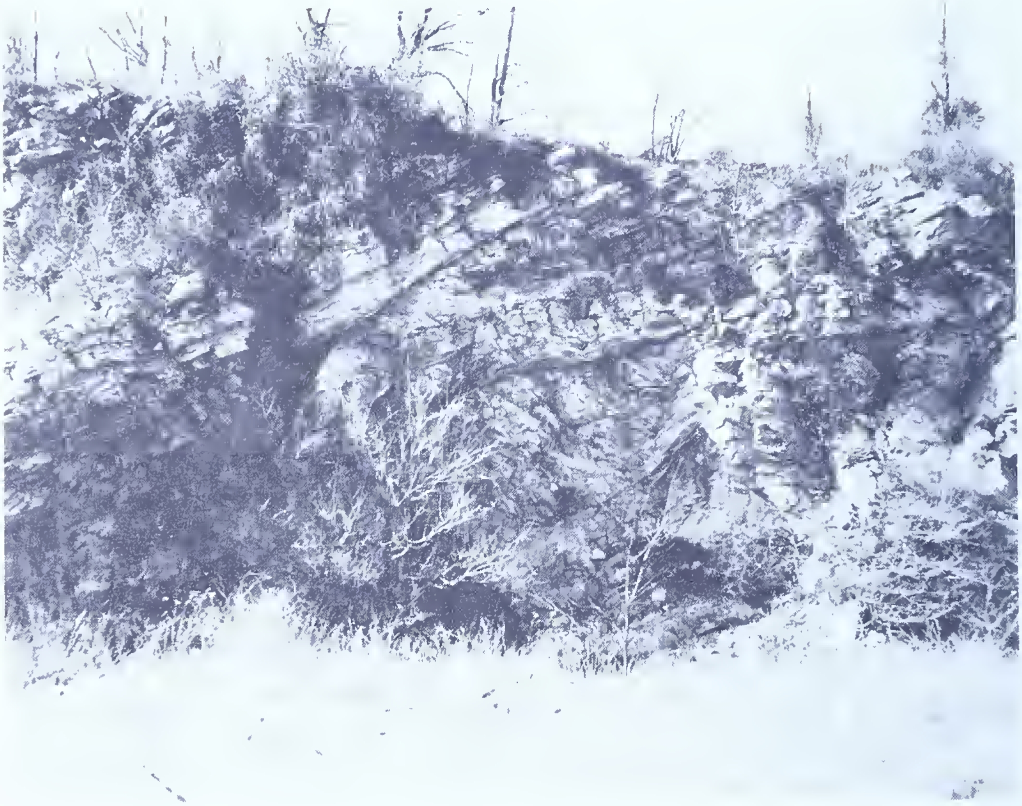

Figure 37. Intraformational thrust faults in overturned beds of Epler Formation. Thrusts are approximately parallel to bedding in the upper plate and are a product of nappe emplacement (Taconic, D_1). Photograph from quarry in southeast corner of Wernersville.

tion is the thrust of intermediate magnitude (between 100′ and 1000′ displacement) about 3000 feet north of Sinking Spring. This fault brings up the Ontelaunee-Epler contact which leads to its detection, though the thrust is nowhere exposed. Undetected intraformational faults of comparable magnitude may well be present.

Judging by exposure conditions in the neighborhood of the major thrusts and some exposed minor thrusts, the thrust zones tend to be loci of deep weathering. There is accordingly a natural bias against thrust observations, and minor thrusts are probably more abundant than indicated by the frequency of observation. While available data permits only the roughest approximation, it would appear that aggregate displacement on the minor thrusts is quite substantial and may be reckoned as of the same cumulative magnitude as the major thrusts.

Thrusting is a feature of both Taconic and Alleghanian deformation. Some thrusts may have been active at both times.

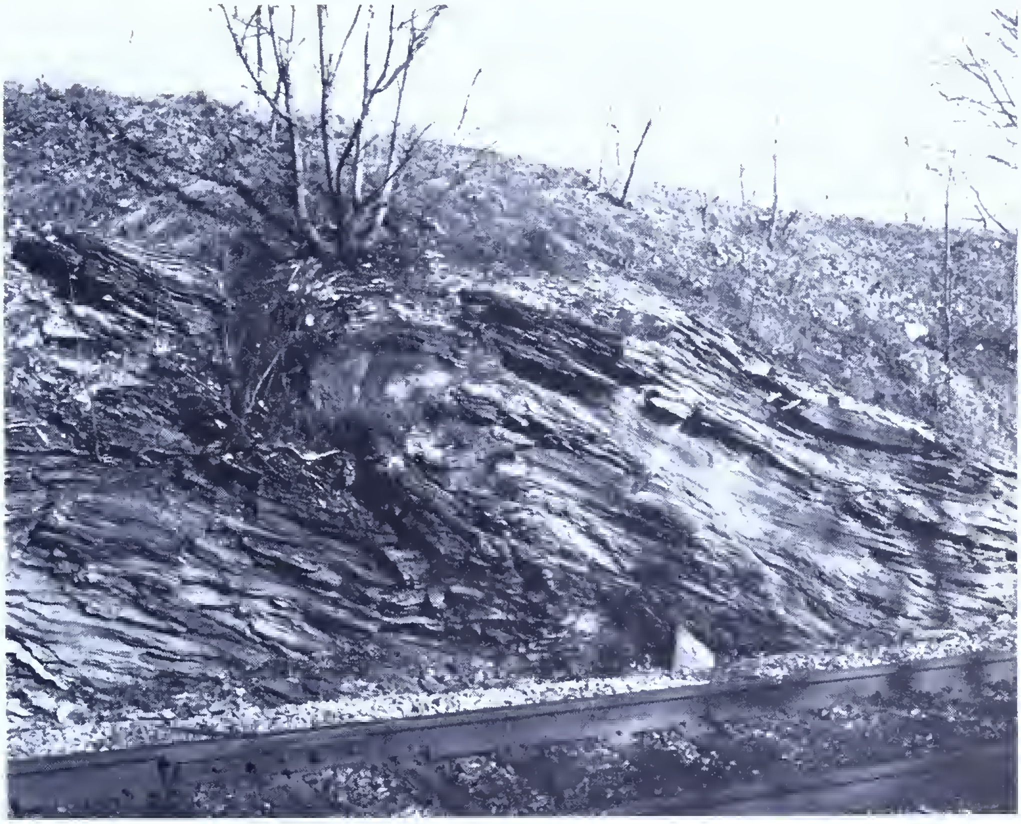

Figure 38. Thrust fault and associated drag folds (B_2^1) in cleavage (S_1) of Hershey Formation. Post cleavage thrusting is a clear product of later stage deformation (Alleghanian, D_2). Reading Railroad cut near Wernersville State Hospital.

High Angle Faults

There are several high-angle faults transverse or oblique to the structural grain, which are apparent in the area of Paleozoic outcrop by their effect on mapped contacts. With the exception of the Hains Church fault, which merits separate consideration, modest vertical displacements of a few hundred feet or less are sufficient to explain the observed lithic distributions. Steep faults parallel to the structural grain have also been observed in exposures but none is known to define a lithic contact within the Paleozoic rocks. They have not been mappable, though displacements may be comparable to that of the transverse faults. The western part of Triassic exposure, at least, is bounded by a longitudinal fault and contains well-developed examples of strike-parallel as well as transverse faults. While some of these faults may represent a special situation restricted to the Triassic basin, it is not unreasonable to anticipate that faults of comparable orientation and genesis may extend into the area of Paleozoic exposure.

Minor high-angle faults with known extent limited to a single exposure are common (Figures 39 and 40), and of diverse orientation and genesis. The majority are so poorly exposed as to permit no reliable determination of attitude or sense of movement, but better exposed examples include steep reverse faults, tears, and normal faults. Stratigraphic displacements are sometimes only inches or feet, but they are often large with respect to the scale of the exposures and not precisely resolvable. Diverse slickenside orientations on single surfaces suggest a complex history of

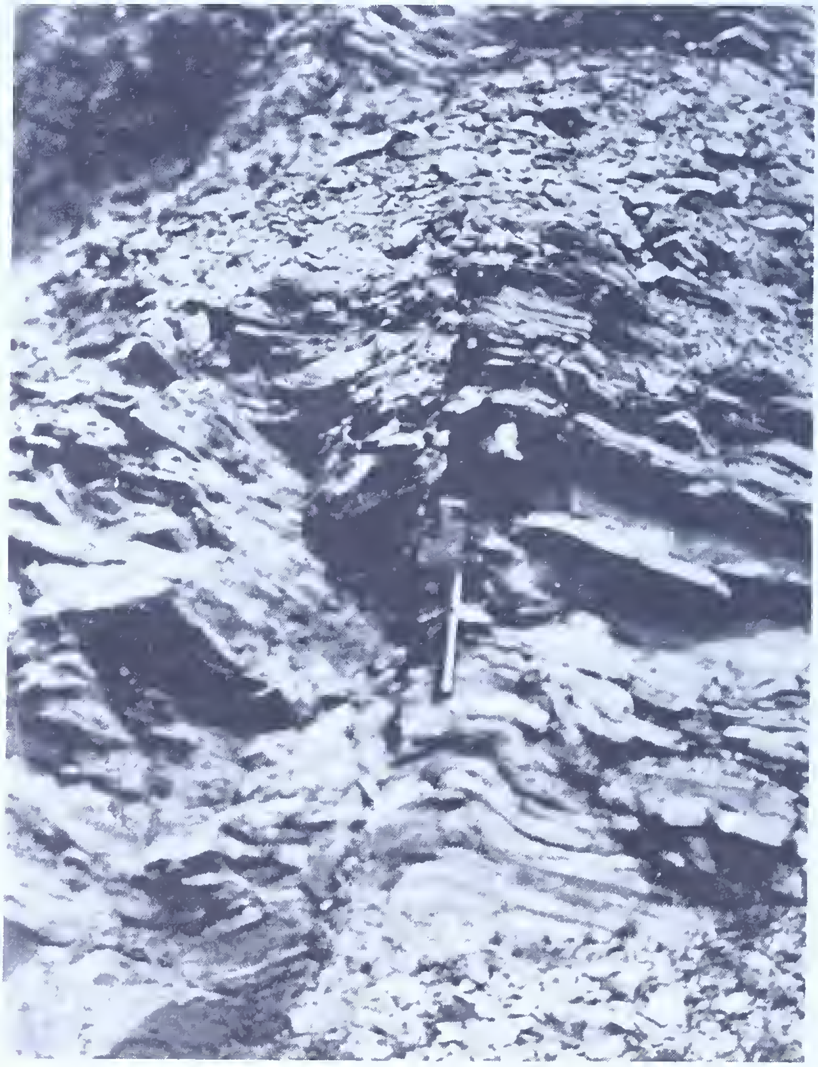

Figure 39. Minor normal fault in Hamburg Sequence limestone.

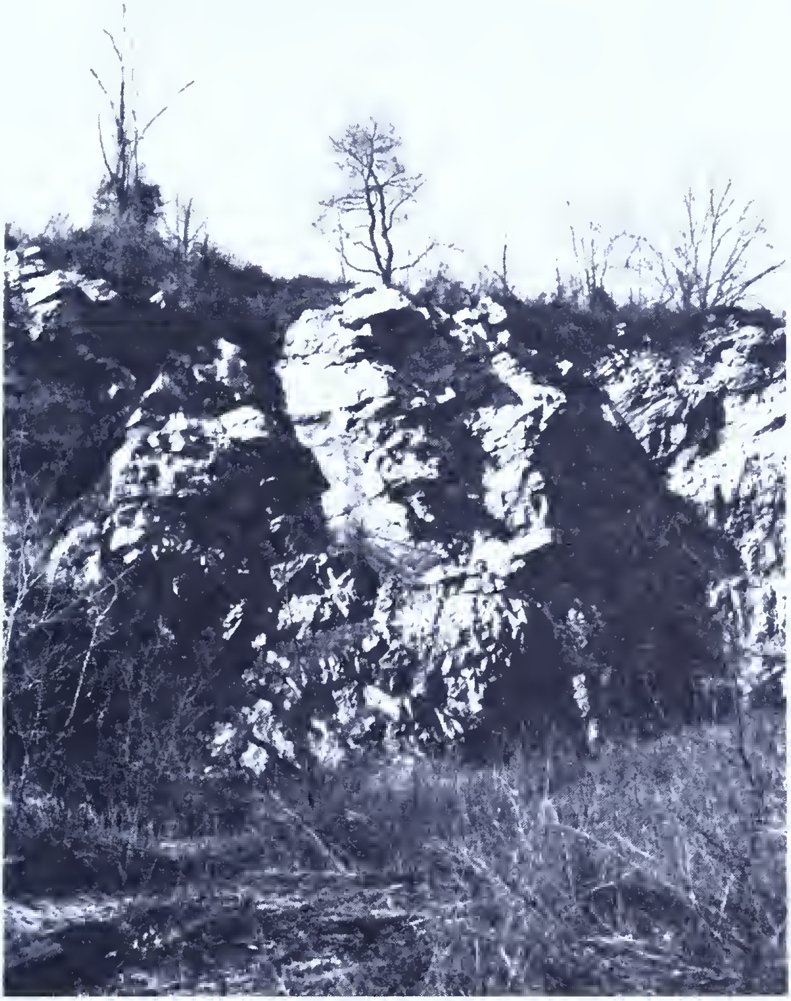

Figure 40. Curved tear fault passing downward into thrust in Epler Formation. Quarry in southeast corner of Wernersville in lower limb of Lebanon Valley nappe. Exposure of the Lebanon Valley nappe is thought to terminate about ¾ mile east by a larger scale fault of the same kind.

minor movements in some cases (Figure 41). Such occurrences are not abundant, but it is reasonable to infer such multiple movements are more common than the preserved evidence, as successive movements tend to obliterate the impress of earlier ones.

The high-angle reverse faults appear to be genetically related to the low-angle thrusting and folding. In some cases subsequent warping or tilting of initial low-angle thrusts may explain the present attitude of the surfaces but in other cases they appear to be ordinary oblique shear fractures parallel to the *b* and inclined to the *a* kinematic axes of the substantial subhorizontal movement involved in the major deformation.

A limited number of observations on normal fault attitudes reveals no clear systematic pattern of orientation (Figure 42). Some correspond with various maxima shown by joint orientation, though it is by no means clear whether they are related in genesis to the joint-forming stresses or are merely oriented by pre-existing weaknesses. Some are approximately normal to fold axes and may well represent *ac* extension fractures. Others are less obviously related to other structural elements. Normal faults are a conspicuous structural feature of Triassic rocks in the Sinking Spring quadrangle and elsewhere in the area of Triassic exposure. The effect of this faulting is presumably not strictly limited to the present area of Triassic rocks, and a significant portion of the normal faulting in the Paleozoic rocks may well be younger than the Paleozoic deformations indicated by compressional structures. On the other hand, structural grain in the Triassic rocks deviates little from that defined by pre-Triassic structures in the older rocks. The clear im-

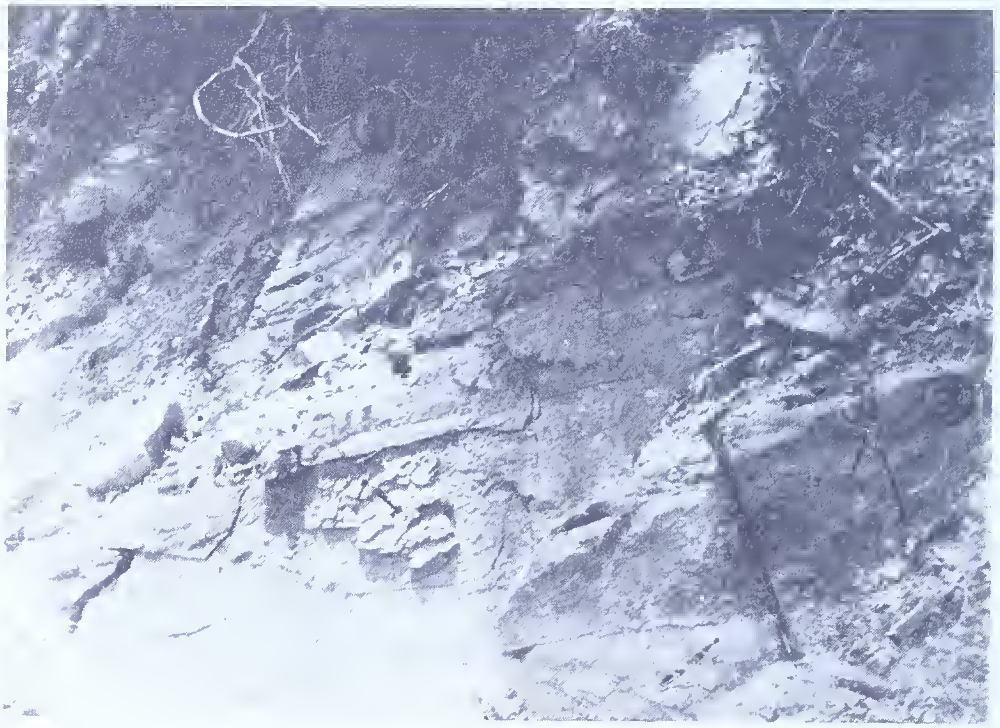

Figure 41. Three closely spaced minor fault planes in the Hamburg Sequence, lithic type 2, showing subhorizontal and approximately downdip slickensides on each surface. Apparent order of superimposition of slickensides is not consistent between the surfaces, suggesting a complex history of minor movements.

plication is that Triassic structures are strongly influenced by the grain of the subjacent rocks, and similar orientation and aspect of faults in Triassic and pre-Triassic terranes is no adequate proof of common genesis.

Several high-angle transverse faults are complexly curved about subhorizontal axes in a manner to preclude any but subhorizontal displace-

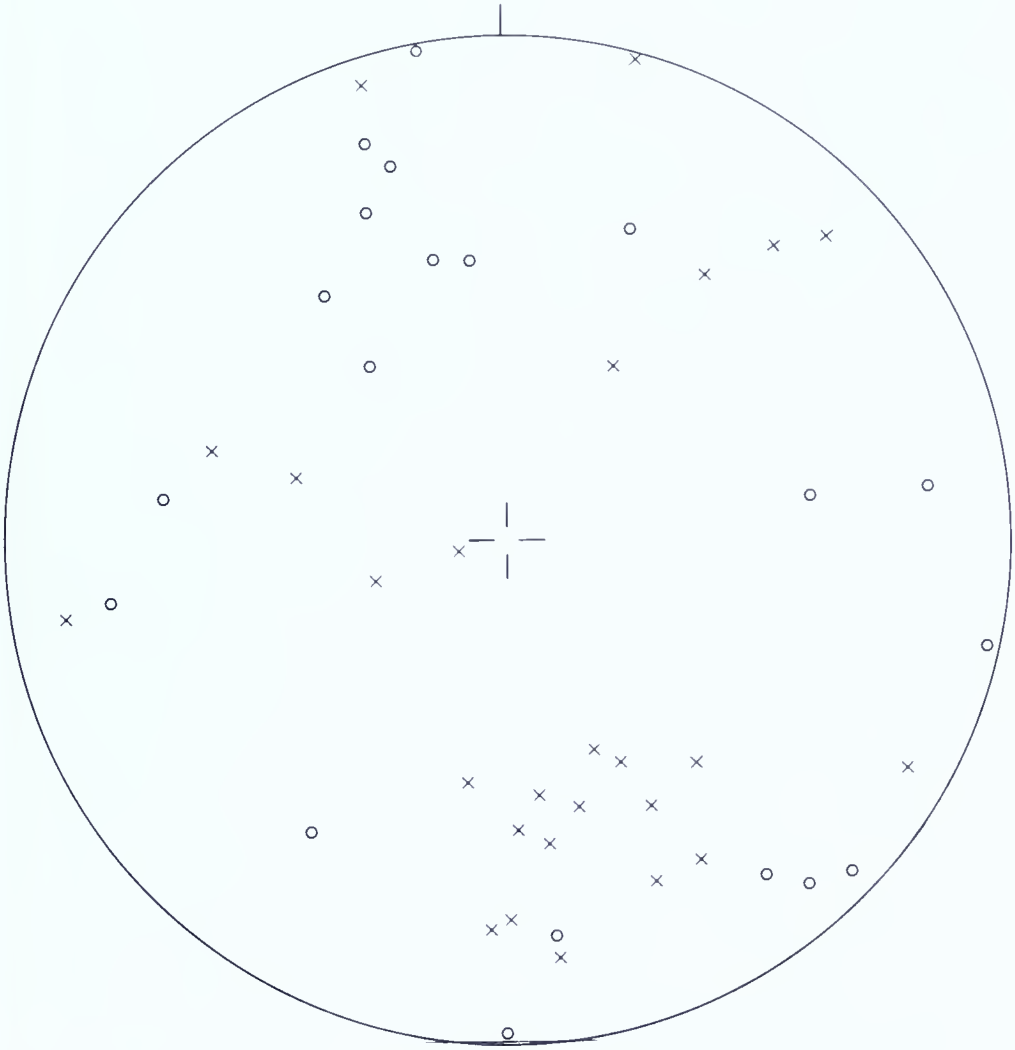

Figure 42. Stereogram of minor fault planes (O) and slickensides (X) measured in Sinking Spring quadrangle. Trend of mappable transverse faults is sparingly represented in this data. While no obviously significant concentrations appear, the majority are approximately parallel to the general lithic grain. The majority of observed slickensides do seem to have an average plunge of about 40° southerly and southeasterly and might be related to D_3 as well as possible earlier minor thrust and tear slip.

ment. Others are more planar but bear subhorizontal slickensides. In some cases the faults clearly curve downward into thrusts as in Figure 41. Well defined tear faults are evidently related to a stage of major horizontal transport and deformation. In the case of minor displacements these tears may simply die out laterally and at depth, but in the case of larger displacements it seems probable that bottoming in thrusts is the usual situation. Suggestions of at least minor horizontal movement are occasionally encountered on strike-parallel as well as transverse faults. However, it seems unlikely that these are tear faults in primary genesis. Minor readjustments on pre-existing fractures between blocks in relatively late deformation is the probable explanation of horizontal movements on these faults. Such movements might also fully account for horizontal lineations on some of the transverse faults. Such horizontal slickensides are not limited to Paleozoic rocks but are also found in Triassic rocks.

Hains Church Fault. The Hains Church fault is the major transverse feature in the Paleozoic rocks of the quadrangle. It is, coincidently or not, aligned with the segment of the Little Muddy Creek fault having the greatest displacement in the same sense. The latter is the major transverse feature of the Triassic rocks. Late movement on the Hains Church fault displaces the Sinking Spring thrust an estimated 250 feet down to the east and is clearly after D_2. North of the Heidleberg thrust, displacement is probably smaller and may be reversed near the Leinbachs thrust. In any case, though the fault reaches the quadrangle line, it cannot extend more than a mile northward (Myers, in preparation). There is an obvious temptation to extend the fault south to join the Little Muddy Creek fault as suggested on the Tectonic Map (Plate 2). Despite colluvial cover, however, there is sufficient control on the contact between the Richland and Millbach Formations to show that it is apparently not displaced by the Hains Church fault, which has not been indicated this far south on the Geologic Map (Plate 1). The alignment of these faults suggests at least common connection to a substantial basement fracture, which may have acted differently in different parts at various times in response to changing stress conditions.

Between the Sinking Spring and Heidleberg thrusts, stratigraphically and structurally distinct rocks of structural levels B and C lie adjacent across the fault, and much larger displacement antecedent to Alleghanian movement on the Sinking Spring thrust is required. This evidently takes the form of a major tear similar in character to the lesser fault illustrated in Figure 40. There is no reason for supposing that such a tear penetrated the rocks of structural level B to any depth. It would appear to be genetically independent of any profound fracture controlling the alignment of the Hains Church and Little Muddy Creek faults. The precise coincidence of the Taconic tear bounding the Lebanon Valley sequence exposure and the later fault is a little puzzling. Indicated displacement of the later faulting does not appear to be sufficient nor in the proper sense to cut off the tear unless it actually curved over to an eastward dip and was coincidently intersected at the right level to produce the observed relations. It is more plausible that the later faulting reactivated the old tear surface, but this does not explain alignment with the Little Muddy Creek fault.

Folds

Paleozoic rocks of the Sinking Spring quadrangle are intensely folded. Folds range in magnitude from crenulations with a wave length of a minor fraction of an inch to the great nappes where a single limb is only partly revealed by exposures extending across a number of quadrangles. The existence of the major nappe systems is supported by numerous structural details in the Sinking Spring quadrangle, but obviously the essential characteristics of these huge structures must be comprehended from larger scale stratigraphic and tectonic synthesis. The scale and style of observable folds is a function of their position in the major nappes and the lithologic, or more precisely, rheologic properties of the rocks. Fold variations by structural position are best demonstrated by comparisons of fold characteristics in the different structural levels summarized later in this chapter. Rheologic contrasts between strata give rise to small-scale variations in fold development in the heavy-bedded carbonates, but the effects are averaged out in folds of sufficient magnitude to involve any appreciable number of beds. The fundamental contrast exists between the heavy-bedded carbonates (Figure 43) and the argillaceous rocks including the Hershey and Jacksonburg Formations.

The shales and argillaceous limestones have well developed, true slaty cleavage which has largely obliterated clear evidence of primary stratification. Isolated minor fold hinges can occasionally be discerned (Figures 24 and 44) which show bulk rock deformation by flow parallel to the cleavage and negligible effects of control by stratification which was passively transposed. Larger scale folding in this style is poorly known. Folds of the Myerstown-Hershey and Hershey-Martinsburg contacts in level C_{3c} are evident on the Geologic Map (Plate 1) and a single nappe digitation of this general type is inferred to explain the lithic distribution in level C_1. Otherwise poor exposure, obliteration of stratification, and a general absence of marker horizons provides little direct indication of folding on scales larger than single exposures. Where the Hamburg sequence contains a significant portion of uncleaved or poorly-cleaved gray-

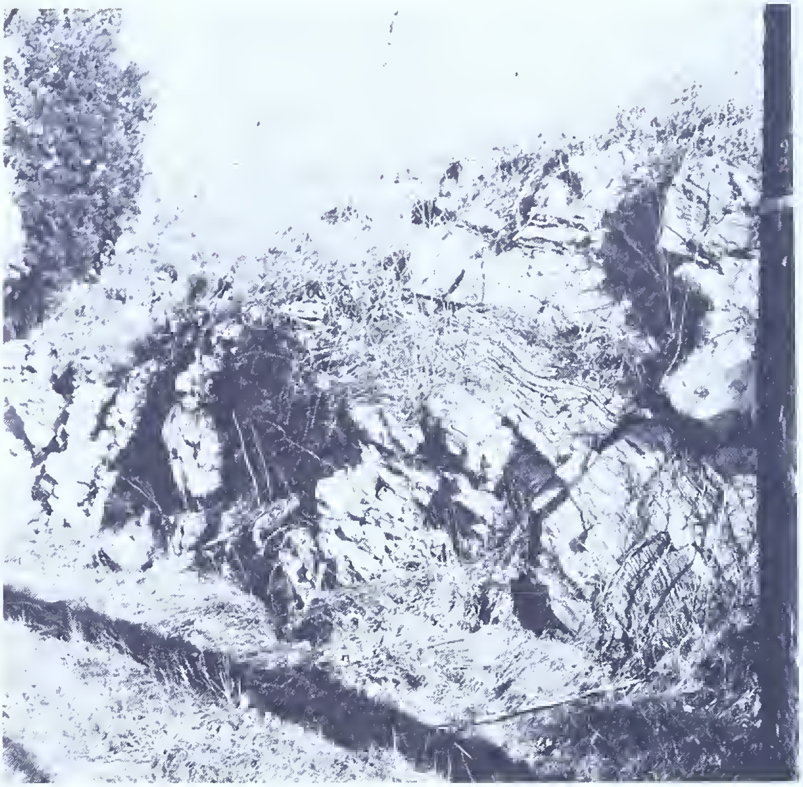

Figure 43. Asymmetric fold (B_1) in Richland Formation. Compare with fold of comparable scale and orientation in shale (Figure 24).

wackes, they may be expected to have a substantial impact on the style of deformation. The poor exposure and indefinite stratigraphic sequence of these rocks makes this proposition difficult to verify. Small scale folding is predictably absent in the scattered exposures except in shaly interlayers. Larger scale folding is implicit in variations between exposures and can be characterized as to axial trend by stereographic methods; but the position and spacing of the hinges commonly remains in doubt.

The majority of fold hinges observed or deduced in the shales are B_1 folds related to the dominant foliation, S_1, though they may have been modified by later deformation. Except for small crenulations (L_{1x2} and L_{1x3}, folding of cleavage was generally not observed at the outcrop scale, though it is implied on a larger scale by areal variation in cleavage dip, as the visible folds indicate no appreciable fanning of S_1.

Folding older than S_1 in the Hamburg sequence was discovered at one place in level B_{2a} graywacke. This relatively minor slice, lying in the sole of the early State Hill thrust, may actually have slid in a semi-consolidated state. Syndepositional tectonism is advocated by recent workers to explain much of the stratigraphic complexity of the Hamburg sequence (Carswell and others, 1968; Alterman, 1969; Myers, 1969, and in preparation, Platt and others, 1969). Additional complications in the bedding geometry of shales in the area may be associated with such syndepositional deformation.

Sometimes folds can be identified with a particular deformational stage by virtue of their definite association with a recognizable cleavage. These provide consistent orientations of folding associated with the later stages of deformation, and provide some basis for assigning other folds to a specific deformation stage on the basis of axial trend where other data are lacking. It will be apparent in the stereograms presented in the structural analysis, however, that there is a considerable range in fold orientation; and such assignments on a purely geometrical basis are somewhat problematical. On the basis of the character and extent of cleavage development and the relation of folds to their structures, it is concluded that the majority of folds were initially formed in the first cleavage-producing stage. Ghosh and Ramberg (1968) have experimentally demonstrated that second stage deforming stress inclined up to 30 degrees from

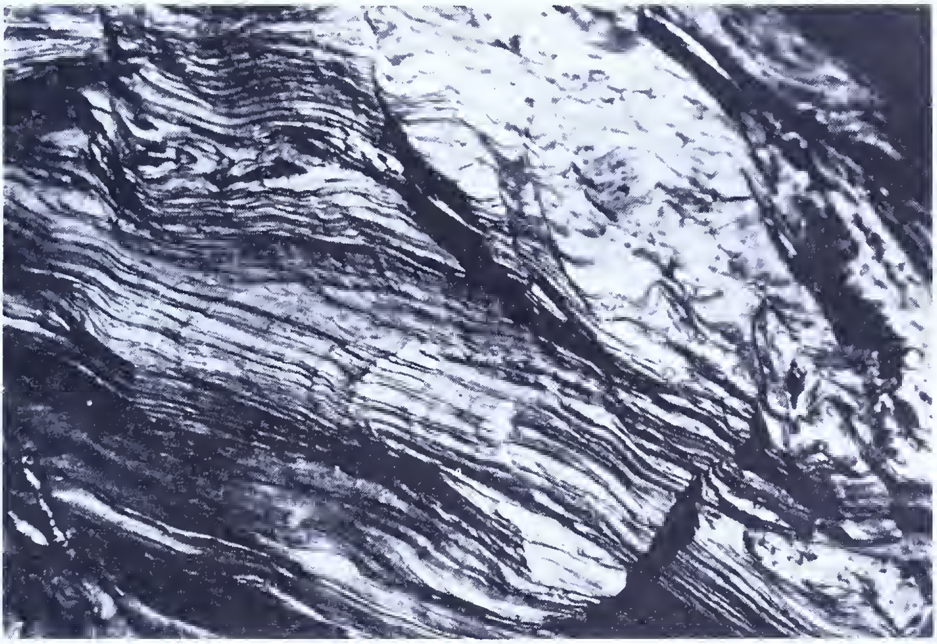

Figure 44. Recumbent fold, B_1, in Hershey Formation. Bedding trace is unusually distinct for this lithology. Prominent foliation is true slaty cleavage (S_1) which is parallel to axial surface and cuts across the structure without fanning. Thickness variation of all layers around fold crest is conspicuous. Limbs become isoclinal and transposed into a vague compositional layering parallel to the cleavage.

an antecedent fold system will tend to reorient the pre-existing folds rather than develop a new system of inclined orientation. A number of minor folds in the B_2 direction appear to be such reoriented folds initially developed in D_1. The considerable scatter of folds in intermediate positions are apparently the result of incomplete reorientation.

Crossfolds (B_1' and B_2'). Experience suggests that many American geologists are not very familiar with simultaneous development of a major fold system and a secondary system plunging down the regional dip, through such a process was suggested to account for certain structures of the Adirondacks as early as 1916 (Martin, 1916). These structures have received considerably more attention from Europeans, especially workers in the Caledonides of Scotland and Scandinavia. Their interpretation gave rise to a considerable controversy with a literature much too voluminous to cite here; but with the publication of a number of highly detailed structural studies in the decade of the 1950's, such crossfolds were widely recognized to be a real feature of a number of complexly deformed terranes, especially in nappe systems. Continuing study and re-examination of older data has led to the conclusion that this type of structure is a normal feature of orogenic belts of Alpine and Caledonian style where substantial nappe movements are involved.

In the Sinking Spring quadrangle crossfolds have been identified which are associated both with Taconic (B_1') and Alleghanian (B_2') deformation. Small-scale examples may be observed in a single outcrop at several places (Figure 45, for example). At a somewhat larger scale their trend dominates stereograms of some small domains located in the vicinity of major thrust faults (Figure 46), and it probably accounts for much of the dispersion of data plotted in other areas. Crossfolds in the form of relatively gentle warps are indicated by a real variation in dip azimuth in several areas with wave lengths in the order of several thousand feet; and the evident curvature of the Sinking Spring and Grings Hill thrusts under the entire South Mountain mass (Tectonic Map, Plate 2) might, indeed, be considered a major crossfold.

Crossfolds appear to be definitely related to a large component of horizontal translation of the rocks in this area. They are associated with mineral lineation on bedding and sometimes on cleavage surfaces which

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Figure 45. Crossfolds (B_2) in the Buffalo Spring Formation near Grings Hill thrust. Figure (a) is a well-developed example with about 40° of flexure. Figure (b) shows more typical subtle development with less than 20° between limbs. Fold axes are approximately parallel to mineral lineation in rock which plunges southeastward down dip.

a

b

plunge about parallel to the crossfold axes. In some cases, at least, penetrative mineral fabric is associated with this lineation (Figures 31 and 49). Both features point to considerable subhorizontal shear in the affected rocks. Well developed examples of crossfolds can be demonstrated only in the vicinity of major thrust faults, where they may be the dominant local trend. The associated lineation is more pervasive, and, as indicated above, subordinate crossfolding may affect a considerably larger body of rocks.

Crossfolding in Hamburg sequence shale was directly observed at only one locality (Figure 46) where it conforms to the underlying limestone. It is implied, however, by areal variation of cleavage attitudes and scattered occurrences of the *a* lineation. Exposure conditions do not warrant extending this generalization, and it is not even certain which deformation may be involved in some cases. Most *a* lineations plunge to an azimuth definitely associated with D_2 elsewhere, and there is a clear impress of D_2 deformation on the shales.

Plunge variation and reversals shown by the large folds mapped in the carbonates of the upper limb of the Irish Mountain nappe (structural level B) may be construed as crossfolding of a sort, but otherwise crossfolding is not evident in these rocks except, locally, adjacent to major thrusts. Crossfolding at all scales seems indicated in the equivalent rocks of the underlimb of the Lebanon Valley nappe (structural level C). This contrast reflects the difference in tectonic position and is an aspect of the structural facies. It is exactly what would be predicted on a theoretical basis if the interpretation that crossfolds in the transport direction are the product of very large componental movements is correct.

Crossfolding associated with D_2 is less pervasive. South of Sinking Spring strong crossfolding is associated with proximity to both Alleghanian thrusts (Figures 45 and 46a and b) but the thick slice of intervening Cambrian limestone is essentially unaffected. Where the slice becomes much thinner adjacent to South Mountain in the western part of the quadrangle, the older fold trend, well preserved to the east, is obliterated or transformed, and folds parallel to the late transport can be discerned in a few exposures. Less extensive B_2' folding is consistent with the considerably less massive plates involved in the D_2 sliding of this area as compared to the nappes of D_1. At their maximum development both involve comparable tight folding, as shown in the full girdle distribution of poles by Figure 47b and c.

Typical exposed crossfolds, illustrated in Figure 45, are fairly open, approximately upright, and symmetric, as is also deemed to be the case for all large scale crossfolds inferred to be present beyond the close proximity of thrusts. The illustrated examples, however, are part of a tighter fold system. In less than 200 feet along the road cut exposing them, distributed readings of bedding show about 90 degrees of rotation between the limbs (Figure 46a). The overall trend of the fold is in good agreement with the axes of the small-scale folds but somewhat inclined to an observed mineral lineation, which is actually more precisely in the average direction of *a* lineation and B_2' in the quadrangle. Additional measurements of the lineation might suppress or remove this discordance, but it is the B_2' orientation here that is more anomalous with respect to the overall pattern in the quadrangle. It might reflect some variation of the D_2 sliding direction with time or some gross rotation of the sliding block about a vertical axis. The mineral lineation is probably a more sensitive indicator of the last movement than the B_2' axis. No such discrepancy exists in a domain of several acres just above the Sinking Spring thrust (Figure 46b), which shows unusually tight folding but is otherwise more representative of the statistical geometry of B_2' folds. The fabric of this domain is clearly dominated by B_2' and involves folding of the Taconic cleavage as well as bedding. In less rotated parts of the area, presence of a perpendicular fold in the B_2 direction is also indicated. Bedding/cleavage relationships suggest that this is reoriented D_1 structure rather than a newly generated fold.

As the relatively small-scale crossfolding becomes tighter it may become markedly asymmetric, with inclined axial surfaces which approach recumbency in places. As seen on individual hinges this seems hard to reconcile with gross transport parallel to the fold axis; but on a larger scale there is no regularity in the direction of asymmetry—hence no regularity in the sense of movement perpendicular to the fold axis. Folds of this type with opposite facing symmetry were designated conjugate folds in the Moine thrust zone (Johnson, 1956). A fold of this type is exposed just below the Lorah thrust (Figure 46c). Data scatter makes the exact trend of the fold a little vague, but a strong tight maximum is generated by construction.

Obvious ordinary small-scale folding of Taconic cleavage (B_2^1) by minor D_2 structures is found in the Hershey Formation near Wernersville State Hospital (Figures 33 and 38). Predominant rotation of S_1 seems to be about a south plunging axis (Figure 46d). This is clearly not parallel to the Alleghanian *a* lineation (La_2), which is well developed in these rocks, but more nearly perpendicular to the average trend of Taconic folds in this exposure (B_1) (example Figure 44). B construction from S_1 in this complexly folded area naturally yields a more diffuse pattern than the preceding example, but it shows several very significant relationships. In the first place, rotation around B_1 (cleavage fanning) and a hypothetical crossfold parallel to prominent La_2 cannot

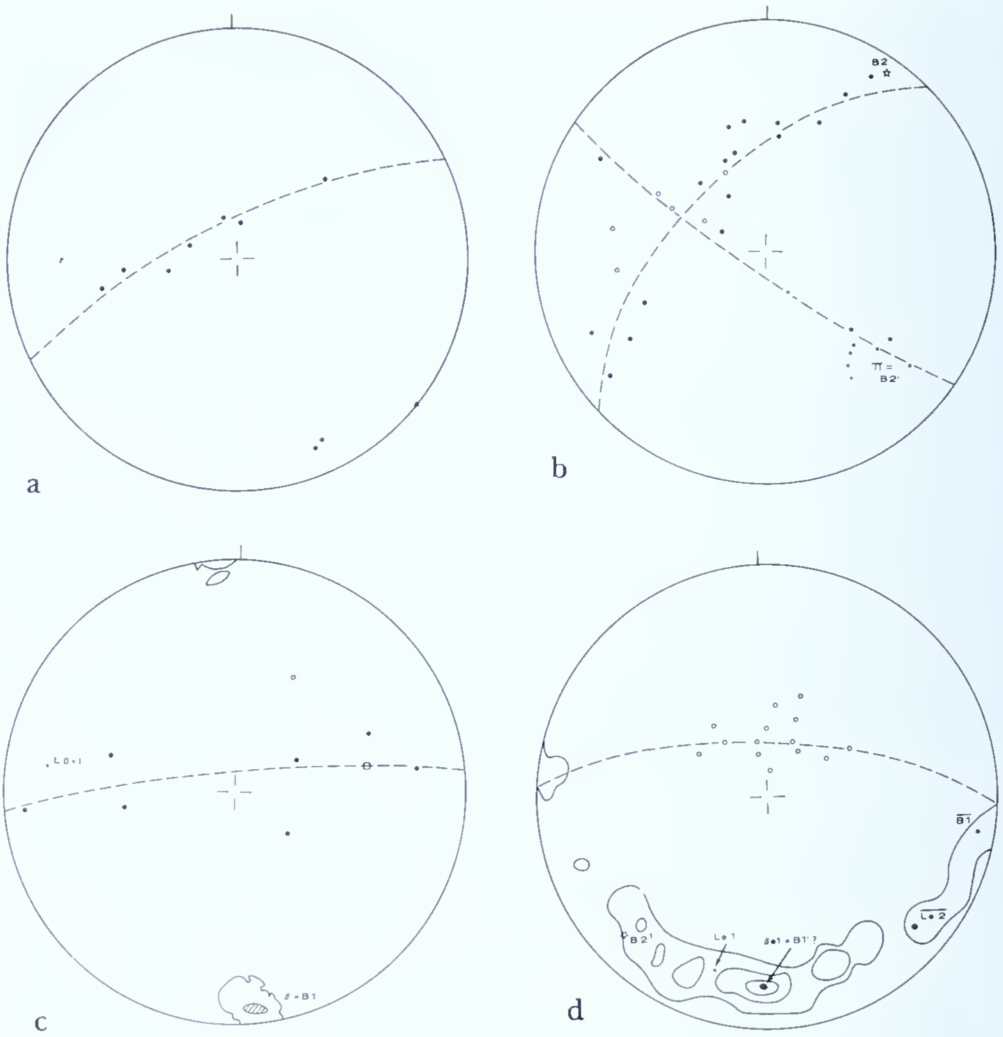

Figure 46. Stereograms of representative crossfolds B_1' and B_2', in Sinking Spring quadrangle. Fold axes shown by stars, except where by construction, designated π or β as appropriate. S_0 closed symbols, S_1 open symbols, lineations by crossed symbols as identified on diagram. See text for details of diagrams and interpretation. a) B_2' fold in Grings Hill thrust zone, structural level D_{2b}, Buffalo Springs Formation. b) B_2' fold just above Sinking Spring thrust, structural level D_1, Richland Formation. Some effect of normal folding about B_2 is also indicated in this domain of several acres. c) B_1, fold just below Lorah thrust, structural level B_1, Ontelaunee and Martinsburg Formations, fold evident in sheared contact and bedding. Axial surface of overturned fold indicated by box, steep west dip on overturned limb. d) B_1' fold in S_1 cleavage in complexly folded area, exposure is not immediately adjacent to any

account for a significant portion of the observed dispersion of S_1 poles. Second, only half as much of the dispersion can be explained by the observed $B_2{}^1$ folds as by the south plunging crossfold. The B maximum showing the latter trend is nearly the same as in Figure 46c; and it is also almost certainly B_1' by this criterion as well as by its near perpendicularity to the local B_1. The implication of this relationship is the unsurprising conclusion that S_1 formed early during nappe transport and was folded during continuing movement. Finally, while there is no obvious significance to the scattered 8 percent submaximum of the diagram other than that associated with $B_2{}^1$, there is an astonishing coincidence. Comparison of the azimuths of the divergent La_2 and B_2 of diagram a (Figure 46) will show that they are identical with La_2 and the southeasterly plunging B submaximum of diagram d. This may be merely pure chance, but it might reflect some aspect of B_2' folding which the author cannot explain. Certainly, since the La_2 lineation is strong and small-scale D_2 thrusting is present in the exposure, B_2' folding is to be considered a possibility. The diagrammed divergence between crossfold axis and *a* lineation is observed in the area of diagram a. One observation of a mineral lineation on cleavage overprinted by La_2, hence presumably by La_1 lies somewhat off the B maximum, and it might tend to support development of crossfolds somewhat inclined to the movement shown by the mineral lineations. The orientation of this single reading however, may simply indicate the kind of statistical scatter of La evident in diagram b.

Lineation

Following the usage of Cloos (1946) the term lineation is applied to repeated linear structures of any scale. It thus applies from the major fold axes which define the grain of orogenic systems to subtle preferred elongation of mineral grains. For the present study attention has been directed to features accessible to direct measurement in the field which have a readily discernible relationship to major structures.

b Lineations. By definition the fold axis defines the *b* axis of a geologic fabric. From a practical point of view it makes no difference whether these are called fold axes (B) or lineations (L_b), though the tendency is to distinguish between them on the basis of whether a single flexure or a repeated (penetrative) structure is evident at the scale of observation.

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known major thrust though not too far from several, located in generally sheared lower limb of Lebanon Valley nappe, structural level C_{3c}, Hershey Formation.

Cleavage developed during folding commonly produces a distinct lineation (L_{0x1}) where it intersects the bedding. Incipient cleavage not readily apparent within a bed may generate a perceptible lineation on the bedding surface. The statistical coincidence of the bedding-cleavage intersection with the trend of an associated fold is well known and is inherent in the mechanics of folding. Cleavage produced by later folding intersects bedding or older cleavage in more complex ways which are fully explicable, but must be interpreted with caution in the light of other evidence.

When an extensional strain component is present in a deformation system, brittle beds may be disrupted into boudins surrounded by more plastic rocks. Examples of boudin development in this area are shown in Figures 14, 25, and 26. Pre-existing joints or other elements of lateral anisotrophy may strongly influence the shape and orientation of such boudins, but ordinarily they will tend to be elongate perpendicular to the direction of extensional strain. There is necessarily a symmetric relation between strain and fabric axes, but the orientation does not invariably produce boudins elongate parallel to B (Ramsay, 1967, p. 112). Within the constrains of the movement picture which is deduced for the Sinking Spring area, the *a priori* assumption of such a relationship seems warranted by the development of B′ folds which assure a compressional strain component parallel to B. Direct measurement of boudin axes was practical in only a few exposures. They generally show good agreement with B or L_b as otherwise determined.

a Lineations. In strictly formal terms the *a* fabric axis is merely the normal to the fold axis lying in the principal fabric plane. Older, fabric-based studies in structural analysis implicitly or explicitly identify this axis with the *a* kinematic axis or direction of tectonic transport. This view is theoretically unsound (Turner and Weiss, 1963) and may lead to consequential errors in interpretation of areas where deformation is largely by plastic flow, and relatively competent layers may have widely diverse initial orientations. In the Sinking Spring area, most structural inferences are based on measurements made in the heavy-bedded carbonate rocks which clearly deformed predominantly by flexural slip or flexural flow (Donath and Parker, 1964); and external constraints on gross tectonic transport directions are provided by known stratigraphic translocations. There are several kinds of lineation which satisfy the geometric description *a* fabric axes and have more or less clear kinematic implications present here. While the analysis may lack certain rigor, it seems evident that these La axes bear a direct relationship to gross rock movement.

Slickensides on bedding surfaces perpendicular to the fold axes provide the most unambiguous evidence. Carbonaceous films in the Myerstown Formation and occasional phyllitic partings in the more massive limestones are sometimes brightly polished and striated. The slickensides are perpendicular to fold axes and are probably the product of interstratal slip during flexural slip folding. However, the possibility that a net northward component of movement in excess of the requirements of the folding derived from distributed movement related to the major thrusting is present cannot be excluded. Owing to exposure conditions in the vicinity of thrusts, probable thrust-related slickensides of this type have not been observed, but the consistent orientation of associated lineations seems to warrant the conclusion that thrust slickenslides would not differ in azimuth from known examples.

A more widespread feature of the same orientation and possible origin is an elongate streaky lineation on limestone bedding surfaces which lack the polish associated with carbonaceous or phyllitic surfaces. Rather similar lineations appear less frequently on limestone cleavage, perhaps because of poor parting on this surface, and sometimes on shale cleavage. Occurrences of this lineation are scattered throughout the limestone terrane, but they are much more abundant in the neighborhood of the major thrust faults. In virtually all cases the lineation is encountered only on surfaces with low to moderate southerly dip, which corresponds to the dip of the major thrusts. In some cases the lineation has a relief of several millimeters and almost certainly seems to be a type of small-scale grooving. More frequently, however, there is little relief and the lineation may be associated with recrystallization. By virtue of their geometric and geographic association with thrust faults, it is almost certain these lineations are slip lines associated with the thrust movement.

These lineations are, at least in some instances, associated with a penetrative linear mineral fabric in the adjacent rock illustrated in Figure 47.

An insufficient sample has been microscopically investigated to warrant the claim that the mesoscopic *a* lineation is always associated with this kind of microfabric; but, at least no contrary example is known. The very strong preferred orientation of the microfabric indicates large componental movements and suggests a considerable amount of distributed shear in the rocks adjacent to the major thrusts. It is expectable that a significant part of this movement will be concentrated on favorably oriented stratification and cleavage planes. The strong mesoscopic lineations on such surfaces are then a more intense manifestation of the processes producing the microfabric.

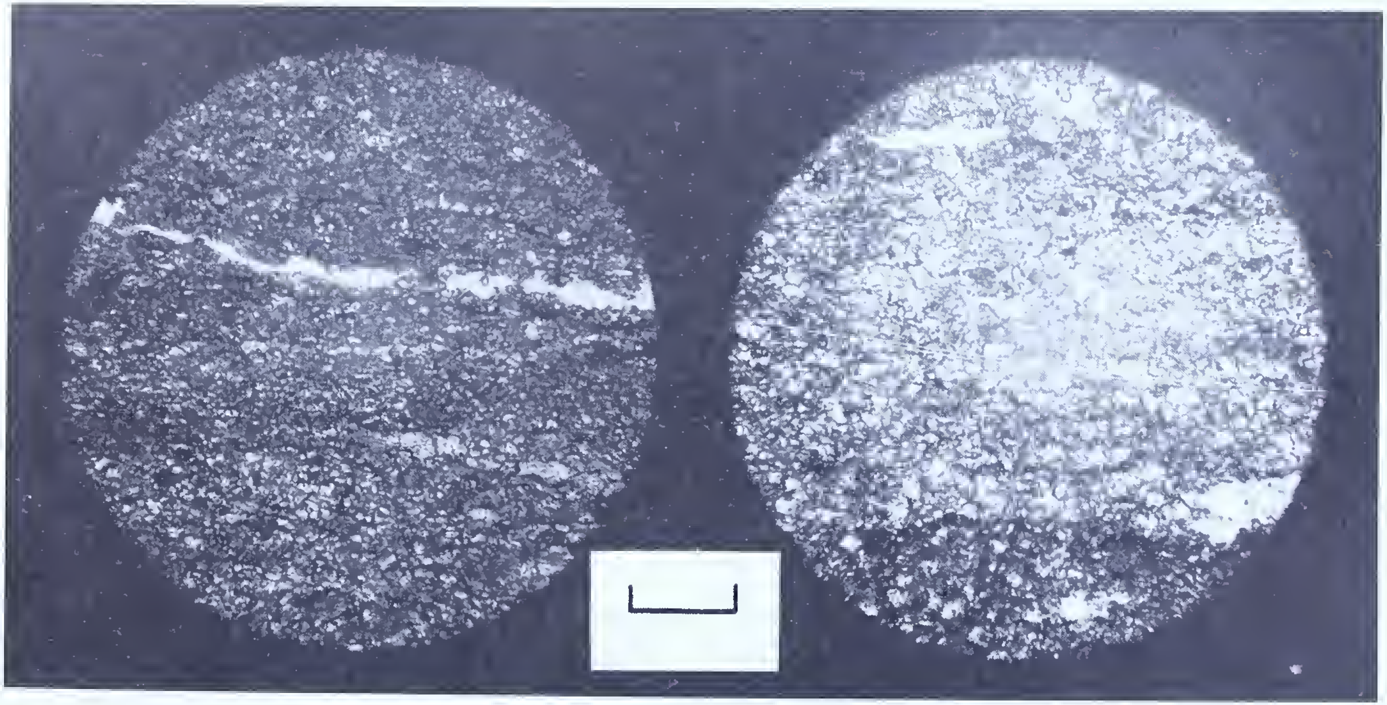

Figure 47. Photomicrographs, grain elongation fabric in Epler Formation. Oriented sections cut parallel to strong "a" lineations on bedding surface and perpendicular to bedding on left, section cut perpendicular to lineation on right. Observe strong preferred orientation of elongate calcite grains in longitudinal section and apparently random or weakly oriented fabric of approximately equant grains in transverse section. Mesoscopic laminae are approximately horizontal in both figures and are shown microscopically by grain size and matrix variations. (Scale length 200 microns).

An indubitable example of the microfabric giving rise to a mesoscopic lineation in less intensely deformed rocks arises in occasional oolitic or pelletoidal limestones. In the illustrated example (Figures 48 and 49) the pellets are near the limit of unaided vision in size and the deformation of individual grains is not readily apparent in the field. There is, nevertheless, a faint but measurable linear grain to the rock which reflects the strong preferred orientation evident in the thin section. The pellet form is evidently a direct reflection of bulk-strain with the azimuth of the elongation corresponding to La as otherwise determined. The illustrated specimen comes from the Allentown Formation of the Temple quadrangle in structural level B_1. It is a particularly good example of development of subtle "a" lineation, but such subtle traces may be observed at several places within the Sinking Spring quadrangle in the upper limbs of the nappes.

The difference between the two microfabrics and their associated lineations is perhaps an essential feature contributing to the difference in general aspect of the upper and lower limb exposures which was characterized as structural facies.

STRUCTURAL ANALYSIS

Geologic mapping and direct observation of relations at individual exposures provides evidence of four episodes of deformation. In the context of available information from nearby areas, certain inferences about the nature and significance of these deformations can be drawn from these observations. The general statement on geologic structure and description of the structural elements provides the substance of most conclusions which may be drawn. Formal geometric analysis permits integrating local detail and defining some aspects of the deformational pattern and history with more confidence than may be obtained by intuition.

Age of Structures

The oldest deformation is represented in the Sinking Spring quadrangle only by rare indications of folding in the Hamburg Sequence older than, and unrelated to, the regionally pervasive cleavage, plus stratigraphic hints of deformation contemporaneous with the Martinsburg deposition in eastern Pennsylvania. Due to the fact that original stratification of the Martinsburg in the Sinking Spring quadrangle has been largely obliterated, sufficient evidence of this early deformation remains only to indicate conditions similar to that inferred elsewhere. This deformation is classic early Taconic in style and stratigraphic age.

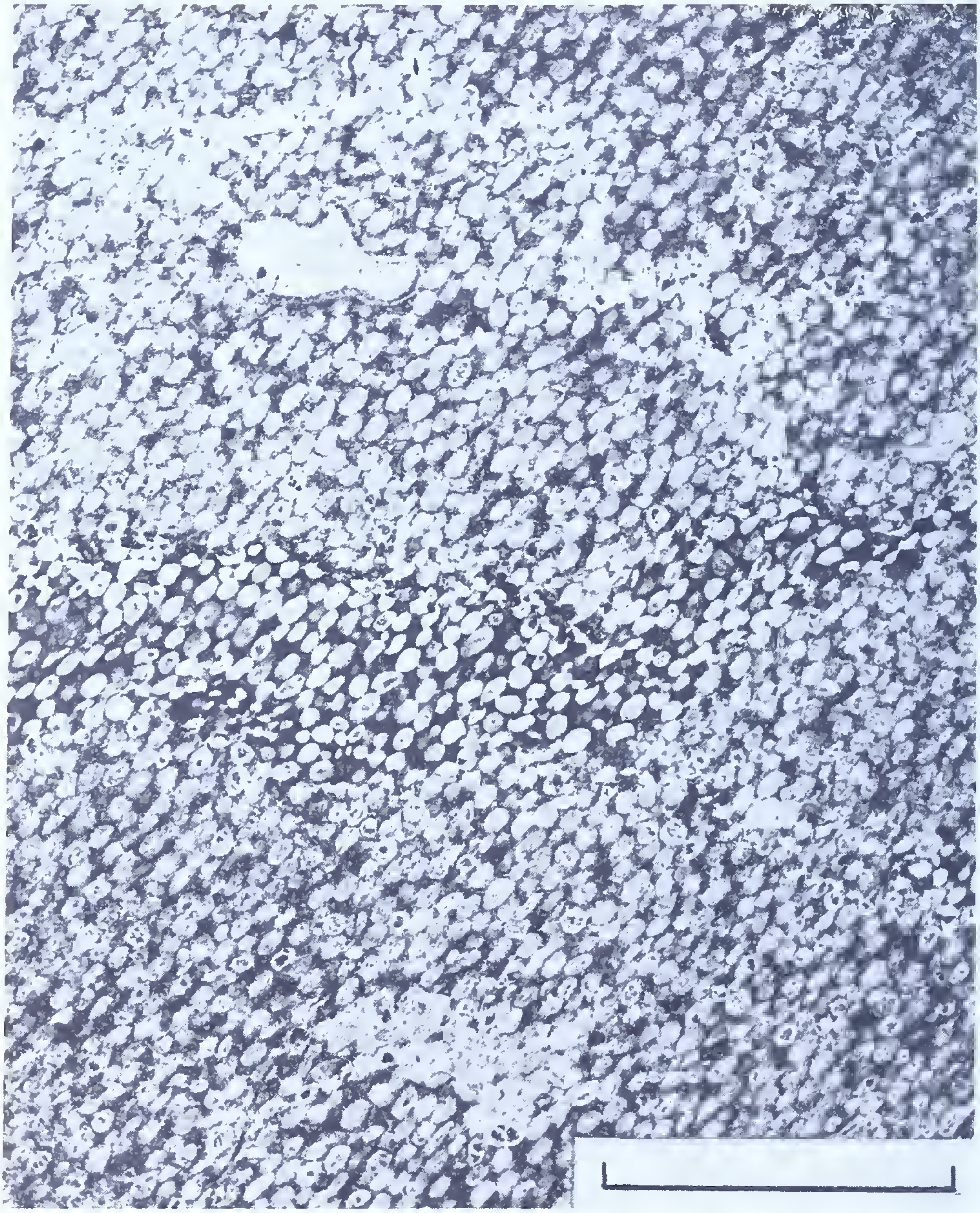

Figure 48. Pelletoidal limestone in the Allentown Formation showing strong preferred shape orientation fabric of pellets reflecting bulk strain of rock. Section is cut perpendicular to bedding and slightly inclined to faint lineation. Direct (negative) print of thin section. (Scale length 0.5 centimeters).

Map relations show a protracted sequence of thrusting. Comparison of exposures indicates the last thrusting in the sequence and its associated folds result from movements differing in orientation from earlier movements. Taconic age structure associated with the Musconetcong nappe is well established by Drake (1969, 1970). His observations are surely applicable along the strike of Reading Prong to the Irish Mountain nappe. MacLachlan's (MacLachlan, 1967; MacLachlan and Root, 1966) case for the Lebanon Valley nappe is less compelling, but the conclusion is the same. Alleghanian age for the younger thrust movements and folds, perhaps is harder to prove by direct evidence; but the presence of Alleghanian folding is hardly to be doubted. Rather it is the Taconic age of the older structure which might have been questioned

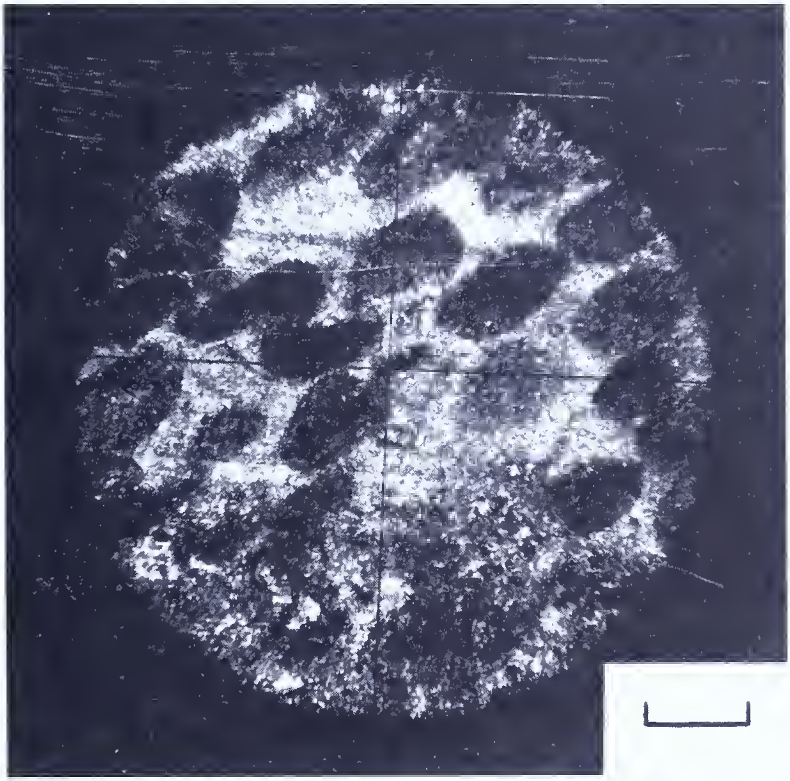

Figure 49. Photomicrograph, perferred orientation in pelletoidal limestone of Allentown Formation. Randomly oriented section has depositional lamination indicated by grain size contrast, horizontal in figure. Rectilinear near horizontal lines are grinding marks on uncovered section. Pellet elongation is inclined to stratification, but there is no obvious orientation of the minute calcite grains composing pellets or matrix. (Scale length 200 microns).

only a decade ago. The map fold pattern shows little obvious effect of the Alleghanian folding, but graphical summary of the data confirms the persistence of a trend which is consistent with type Alleghanian folding in the Valley and Ridge Province.

Minor late compressional deformation is indicated primarily by scattered occurrences of a cleavage younger than the main Alleghanian structures. It seems logical to associate this phase with the uplift that must have preceded or accompanied the extensive erosion occurring prior to the deposition of the Upper Triassic continental sediments. The late cleavage is quite constant in attitude and has a strike parallel to the structural grain of the Triassic basin; however, there is no suggestion of this surface in the Triassic rocks. The event can only be dated on this basis as pre-Upper Triassic; but, by its compressional character, it would appear to represent a late phase of the Alleghanian orogeny.

High angle faults, some of considerable magnitude are found within and at the margin of the Triassic basin. Some faults of comparable orientation are known in the Paleozoic rocks and may be the same age; but none of these has been actually observed to cut the Triassic border.

Formal Analysis

Greater precision about the prevalence and persistence of various structures and structural trends, and their mutual relations, hence of the movements affecting the rocks, may be obtained by statistical geometric analysis and synthesis. The essential technique employed here is to bring together measured attitudes of structural elements on diagrams in which the attitude of each element observed is recorded as a point. The circular diagram represents a map of a hemisphere which extends beneath the plane of the diagram. Each linear element (fold axis or lineation) is conceived as pasing through the center of the hemisphere, and the recorded point represents the intersection of this line with the surface of hemisphere. Surfaces (beds, cleavage, etc.) are recorded as the point of intersection with the hemisphere of a line perpendicular to the surface passing through the center of the figure. The symbols used to distinguish between the different elements plotted in these stereograms presented here are shown in Table 2. Only in special cases are they specifically identified in the figure captions or text. Readers not familiar with such diagrams are unlikely to grasp all their implications, but it should be noted that there are certain groupings of particular types of data for which explanations will be attempted. The analytic results provide a basis for conclusions which are more specific and more precise than those obtainable directly from the mapping.

In mapping the quadrangle, where possible, at least one good exposure containing structural features thought characteristic of the area was studied in considerable detail in each structural level. A good example of the structural data and its treatment is shown in the stereogram, Figure 50, for data from the cut on Fritztown Road about 2000 feet southwest of the Reading Railroad main line. Various features of this exposure are illustrated in Figures 26, 28, 34, and 43; and it is of particular interest because it is a rare carbonate exposure where relationship between all three episodes of deformation may be seen. Data from surrounding areas were then added to that of the master station extending as far as major structural trends persist without substantial variation. The stereogram of Figure 53a shows data from all of structural level D_1 east of the projected trace of the transverse fault passing through Sinking Spring Borough. A different structural domain exists to the west, but the fault is coincidental. Despite several thousandfold difference in the

Table 2. *Symbols Used in Stereograms*

●	Bedding (S_o)	
○	Cleavage (S_1)	
□	Cleavage (S_2)	
⧄	Cleavage (S_3), also on figure 51. ◪	
★	Fold axis (B)	open symbol younger, where 2.
☆	Fold axis (B)	
⊗	L_{ox1} or other L_b lineations.	
×	Intersection lineation—usually L_{1x2}, L_{1x3}, L_{ox2}, L_{ox3}	
▲	La lineation	open symbol younger(?), where 2.
△	La lineation	
⍟	Crossfold axis (B′)	
π	Statistical fold axis derived from girdle of planar elements.	

areas represented, it will be observed that, with the exception of La_2, the dispersion of the various elements from their trends in these two figures is almost identical. This fact has the extremely important implication that the observed variability of the data is an intrinsic property of the local structural fabric, and that this fabric persists without appreciable statistical variation over large areas. It is this property which makes theoretically justifiable the synoptic diagrams which summarize the deformational effects over the entire quadrangle and provide an objective basis for identifying certain orientations of structures with particular ages of deformation on a quadrangle-wide basis.

No single trend is dominant throughout the entire quadrangle. West of the area covered by Figure 53A, exposures in structural level D_1 yield an entirely different trend than to the east. Diagram B of this figure represents structural data from level D_1 to the west, where an entirely different fold trend dominates the fabric. The small domain of Figure 46b may be considered a local type equivalent to Figure 50 for the preceding example. Diagrams like those of Figure 53 for all or large parts of all structural levels provide the basis for structural generalizations in their description.

Deformational elements in the areal fabrics were then collected on diagrams for the whole quadrangle but separated by deformational age. This yields the summary diagrams showing the symmetry of their fabrics from which probable orientations of major movements can be deduced.

Late Alleghanian Deformation (D_3)

The essential element which serves to indicate the last minor penetrative deformation is a crenulation cleavage (S_3) sporadically encountered in the structurally sensitive argillaceous rocks. Parting along this cleavage is generally poor, but its presence is indicated by crenulate intersection lineations on other surfaces. The appearance of this cleavage does not differ from typical development of an older crenulation cleavage (S_2) in the same rocks, but only in a few more questionable cases has a surface been identified as S_3 where S_2 is not also present. Typical exposures showing two crenulation cleavages provide no clear evidence of their relative age, but one example of S_2 crenulated by S_3 has been encountered while the reverse is not known. The relatively late age of the S_3 surface is clearly implied by the synoptic diagram Figure 51. In this figure twelve determinations of the attitude of S_3 in scattered shale exposures are distinguished by half solid symbols. These define a distinct maximum with only 24° between extreme values. Crenulation lineations—mostly L_{1x3}—from many exposures are spread along a girdle to which the S_3 maximum is polar, and show a comparable variability normal to the girdle trend. This variability is small relative to that of other elements measured in the shale terrane. The conclusion is that the D_3 elements are undisturbed by subsequent deformation and are distinctly younger than all other more variable elements.

Small scale crenulations such as commonly accompany S_2 and S_3 in shaly rocks are infrequently developed in calcareous rocks even where a late cleavage is definitely present. As in many shale localities the presence of S_3 is indicated only by the presence of the crenulation; it is not remarkable that D_3 effects of comparable intensity are not recognized in the carbonate rocks. At a few localities, somewhat coarser folding appears in argillaceous beds of the Richland Formation (Figure 34). This folding is clearly a relatively late feature which has an axial surface parallel to an incipient cleavage substantially identical in attitude to S_3 surfaces in the shales. Direct evidence that these surfaces are in fact younger than S_2 elements appearing in the same exposures is lacking; but the geometric similarity between occurrences argues a common genesis. Seven measurements of S_3 in the exposure including the rock illustrated in Figure 34 have a somewhat greater variability—about 36° between extreme values—in this small area than was observed throughout the shale terrane. Six S_3 attitudes obtained from other Richland Formation exposures actually differ less from attitudes obtained in the shale.

There is an obvious contrast in mechanical anisotropy between the quite uniform argillites which ordinarily show S_3 and the interbedded limestones, dolomites, and occasional calcareous shales of the Richland Formation. It seems almost certain that the somewhat greater variability of S_3 in the Richland Formation is a consequence of local stress reorientation by this anistropy rather than any fundamental difference in the overall generative stress field.

The tendency of lineations and minor folds associated with S_3 to have a great circle distribution on the stereogram is the result of superposition of S_3 on diversely oriented pre-existing surfaces. The fact that the majority of observations have a low to moderate easterly or westerly plunge is significant only of preferred orientation in the antecedent structural grain. The similarity of S_3 strike and the dominant Taconic grain (Figure 37) would probably cause any larger scale folding in D_3 to be indistinguishable from D_1 folding, unless D_2 elements were recognized to be affected.

Some indication of rock movement, probably greater than the minimum necessary to generate S_3, is provided by rare occurrences of a slip lineation demonstrably younger than La_2 by direct superposition. Similar lineation less directly dated appears in the stereogram for shales of structural level B_2 (Figure 55B). As this lineation appears on S_1 in

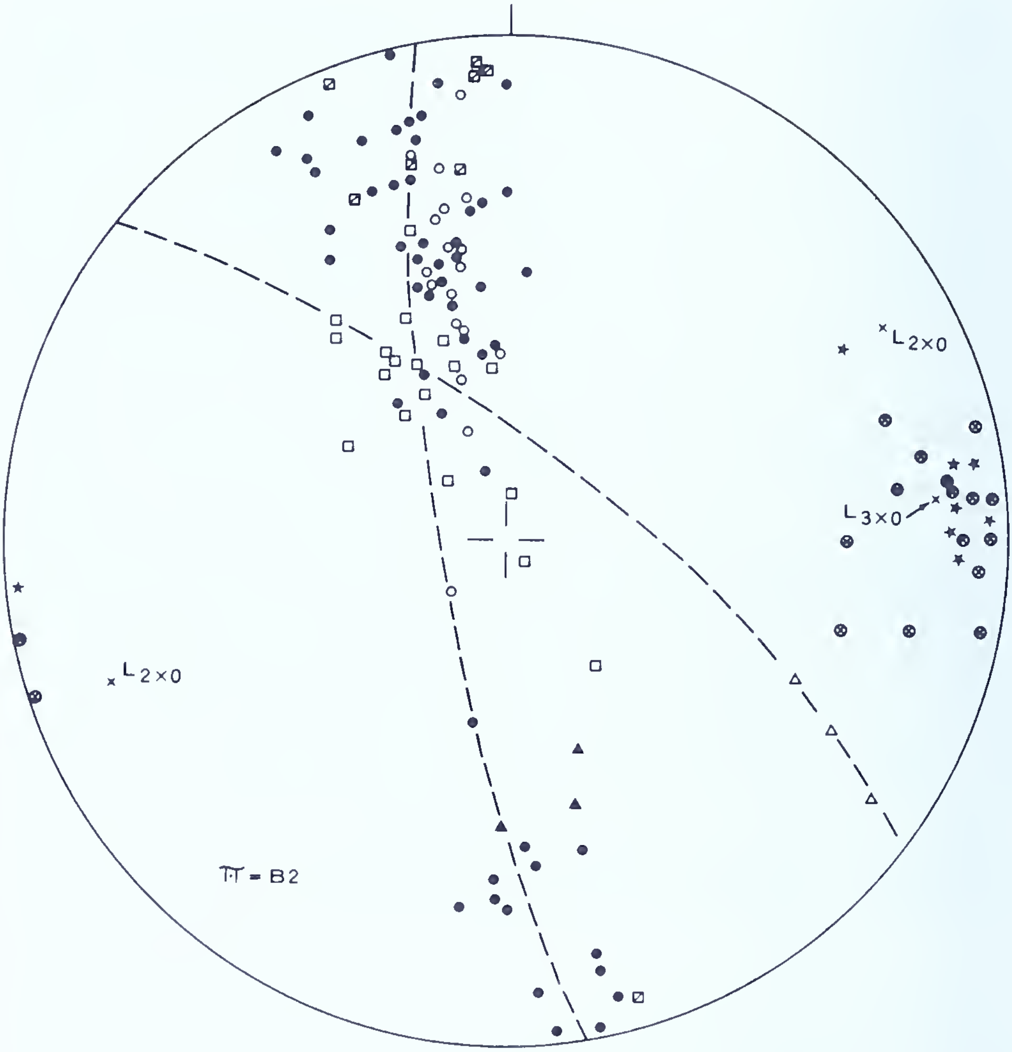

Figure 50. Structural fabric in rocks in Richland Formation in cut on Fritztown Road about ½ mile southwest of Sinking Spring. Fabric is dominated by simple fold (B_1) shown by girdle of S_0 and S_1 normal to cluster of measured minor fold axes (B_1) and Lb_1 lineations. Impress of later deformation shown by inclined lineation La_2 and fracture cleavage S_2 does not appreciably modify the major structure. Girdle fitted to D_2 elements indicates a local rotation axis (B_2) associated with D_2 which is the hypothetical axis of folds that would be formed in flat lying strata by the implied movement, but it does not necessarily coincide with L_{2x0} formed in strata inclined before D_2. Late crenulation cleavage S_3 is associated with small folds in S_1 (Figure 34) which have axial orientation about parallel to measure L_{3x0}. Deformational sequences D_1-D_2 and D_1-D_3 are clearly demonstrated by field or geometric relations; the sequence

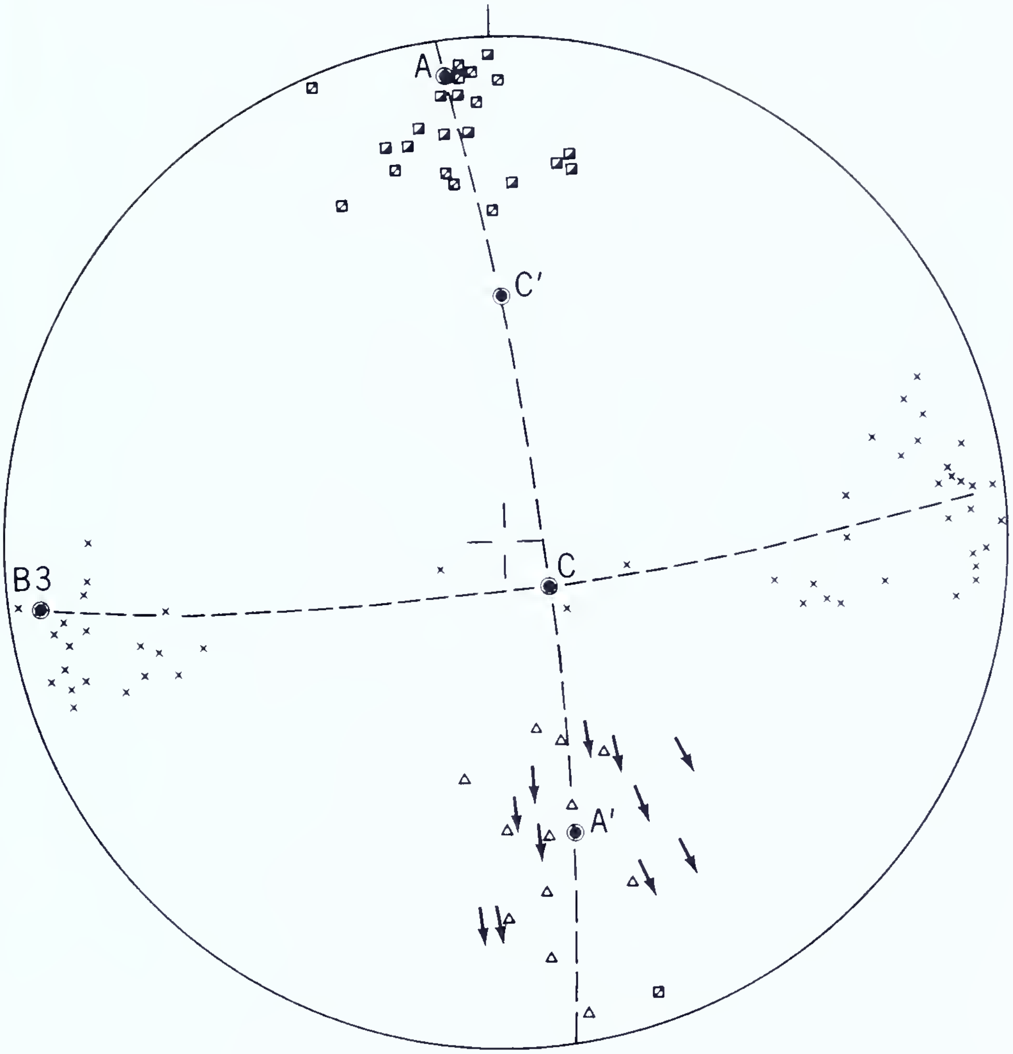

Figure 51. Synoptic diagram of D_3 fabric elements in Sinking Spring quadrangle. S_3 in shale distinguished by half solid symbols. Lettered points are deduced kinematic axes of the deformation. Arrows represent minor fault slicks with southerly plunge taken from Figure 42 for comparison with La_3. Other symbols as in Table 2. The girdle BC is visual best fit for the trace of mean S_3 as defined by L_{3x1} and other intersection lineations. A is the BC girdle pole and the AC circle is fitted through A and the mean of La_3. (See Plate 3 for detailed diagram)

D_2-D_3 is not provable here, but follows from its uniform attitude in areas where D_2 folding is strong.

this area and the rocks have been considerably affected by D_2, survival of La_1, which might reasonably have this orientation, seems improbable; and they are probably the same as the few known late lineations, which also have this azimuth approximately normal to strike of S_3. Barring an improbable two-fold deformation after D_2 with at least roughly comparable strain orientations implied, the slip lineations are almost surely cogenetic with S_3 and are La_3.

Minor faulting in the area not directly related to major thrusting is probably in large part later than D_2 on the basis of apparent truncation of D_2 elements in a few cases and map relations of the few larger transverse faults. While the coincidence does not prove common genesis, it may be noted that the principal concentration of slickensides recorded in Figure 42 plunges to the south. The distribution of this group of slickensides is also shown in Figure 51 for comparison with La_3. No sense of apparent displacement was recorded in association with any of the slickensides, but their orientation is at least consistent with the proposition of a reverse fault developed at the Triassic border during D_3.

Another possible effect of D_3 might be the joints forming the relatively compact concentration labeled "A" and "B" in Figure 36. These are evidently formed relatively later than joints that appear to have orientations systematically affected by D_2 and are roughly normal to an extensional strain component which could be inferred parallel to the rotation axis implied by translation along La_3.

In view of the fact that the shales from which most of the D_3 data were derived are evidently homogeneous in deformational response, full kinematic analysis does not seem too speculative. The azimuth is clearly specified by La_3. If componental movement in the bulk of the rock is actually parallel to La_3 the *a* kinematic axis is approximately the point A′ of Figure 51. S_3 is suitably oriented to represent a pure shear plane in this case, but the conjugate pure shear plane is unknown. The S_3 poles and the lineations define the deformation plane A′C′; and the pole of the conjugate to S_3 should lie in A′C′ symmetric with respect to A, that is, gently south dipping. No such planes are known, though they would probably have been distinguishable from other surfaces had they been present in anything like the abundance of S_3. Since compressional strain component perpendicular to S_3 is demonstrated by the minor B_3 folds shown in Figure 35, it cannot be argued that a gravitational stress component favored only the S_3 set of a conjugate shear pair. It follows that S_3 is not a pure shear plane associated with movement parallel to La_3. The alternate interpretation that D_3 componental movements were statistically near horizontal, producing a minor fold system, is self evident in the area of the photograph (Figure 34), but because of the inhomogeniety of the Richland Formation that conclusion cannot be carelessly generalized to the shales. In light of the preceding considerations, however, it does seem correct. The bulk kinematic axes are then *a* (A of diagram) perpendicular to S_3, plunging about 8° to azimuth 352°, *b* (B of diagram) is normal to the deformation plane and plunges about 6° to azimuth 265°, and *c* plunging about 80° to azimuth 139°. The La_3 slip lineations are, in this case, to be interpreted as the affect of slip under the influence of pure shear on favorably oriented antecedent planes. In this movement geometric preferential development of the upward shear is often observed, and single orientation of slip linears is not remarkable. Indeed, if this deformation maintains the Alleghanian D_2 pattern of net northward transport and is associated with post D_2 uplift, preferential shear in this direction is obviously indicated. This correlates perfectly with reverse faulting which was previously suggested to be related to D_3.

Alleghanian Deformation (D_2)

Late thrusting, as defined by superposition, is obviously associated with a lineation La_2 at several exposures. This lineation has some local variation, but its statistical trend persists, and clearly indicates the direction involved in the thrusting. Other structural elements clearly younger than folding and cleavage of the first deformation, with the exception of D_3 elements already discussed, have an obvious geometric relation to the movement indicated by La_2, as shown in the synoptic diagram, Figure 52.

Intersection lineations shown on the diagram are predominantly L_{2x0} where measured in carbonate rocks and L_{2x1} where measured in shale. Owing to prior deformation, the orientation of these lineations will depend on chance attitudes of the surface intersecting S_2. Although S_2 has a wide range of dip, as its strike remains about perpendicular to La_2, the mean statistical orientation of the intersections will approximate the B_2 rotation axis implied by the known translation parallel to La_2. The orientation range of S_2 is somewhat puzzling. It cannot be a single surface formed early in D_2 and subsequently rotated through this range because the maximum rotation about B_2 which can be allowed from rotation of the antecedent surface S_1 in Figure 53a is appreciably less than required to produce the spread of S_2 in the same figure. If S_2 developed as conjugate shears early in D_2 movement the allowable rotation is perhaps just sufficient to produce the observed distribution. This possibility is supported by the fact that the closest approach to a discontinuity in full girdle distribution of S_2 poles is a possible gap

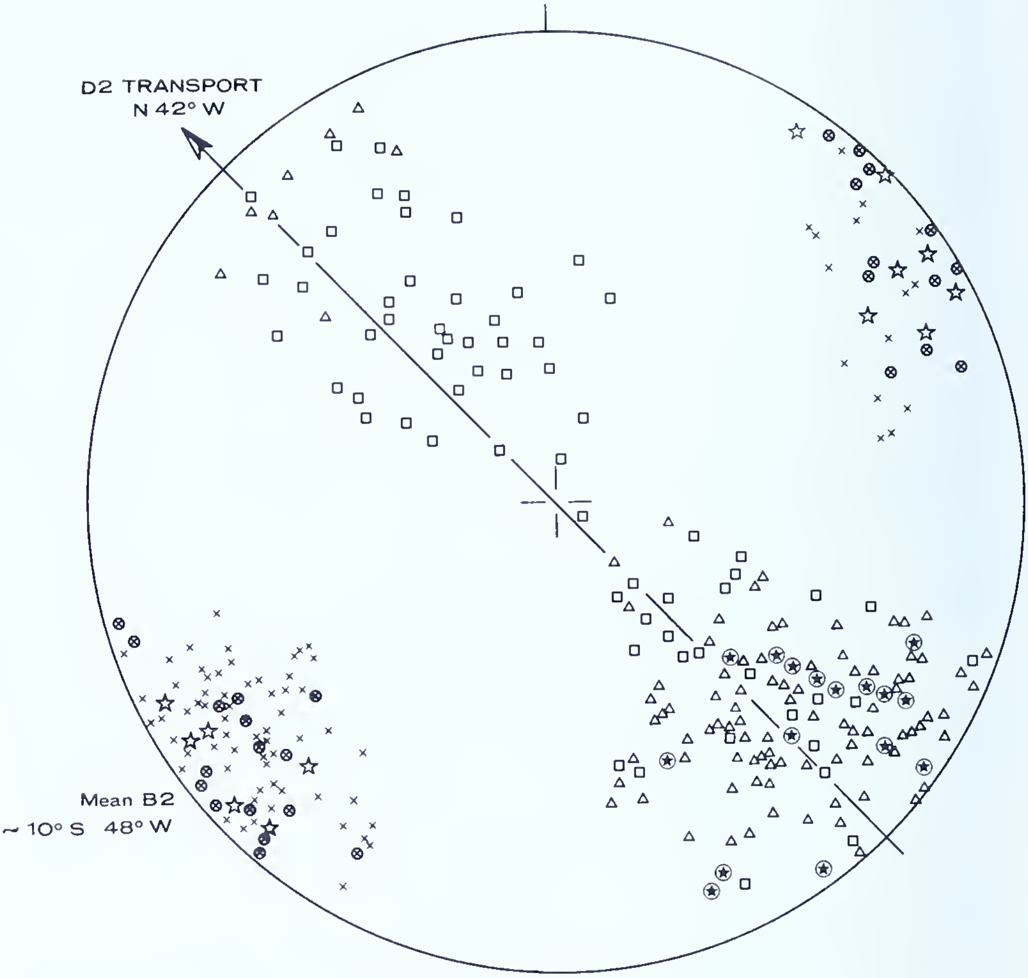

Figure 52. Synoptic diagram of D_2 fabric elements in the Sinking Spring quadrangle. Symbols in diagram identified on Table 2. Some folds, normal to La_2, are original D_2 structures but L_{1x0} lineations and some folds appear to be reoriented D_1 structures. Cross folds parallel to La_2 can be more readily distinguished from D_1 structures by their orientation. Complete girdle defined by S_2 poles is obviously related to D_2 movement but mechanical explanation is uncertain. Intersection lineations recorded are predominantly L_{2x0} from carbonates and L_{2x1} from argillaceous rocks. (See Plate 3 for detailed diagram)

between NW and SE dipping sets, but this gap is only 25° with one intermediate pole.

The major problem of interpretation is in the character of the folding developed in rocks already strongly folded during nappe emplacement. Minor folds in S_1 clearly related to S_2 cleavage or minor D_2 thrusting have already been illustrated. Features of this scale, however, will have little direct effect on the major folds. Ghosh and Ramberg (1968) have experimentally demonstrated that bucklefolds, which is the essential character of all substantial folds in the carbonate rocks where such folds can be best defined, will tighten and reorient in response to subsequent stress unless maximum compression is inclined less than 60° to the original fold axis. With sufficient strain, folds reoriented perpendicular to the maximum compression are possible, but lesser strain can produce any orientation intermediate between that orientation and original orientation of the antecedent fold axis. Tightening of folds in D_2 is clearly indicated by comparing the tight overturned syncline near Sinking Spring in structural level B_3 just below the Alleghanian thrust plate of level D_1 with the mcre open anticline in level B_1 to the north. In fact, as the Sinking Spring thrust overrides this syncline in the Reading quadrangle, shale is evidently extruded from the synclinal core into the thrust surface, to develop the structural level D_{1a} of the Tectonic Map (Plate 2).

Fold axis reorientation is certainly implied by the existence of folds in Figure 52 having the approximate orientation predicted for B_2 from S_2 and La_2, but with the uncertainty of antecedent fold trends in the face of multiple deformation, these folds could conceivably be in their original orientation. The question of fold reorientation is best examined by considering some examples for evidence of reorientation.

Folding in the eastern part of structural level D_1 (Figure 53a) is clearly dominated by a simple form related to S_1 cleavage. Sufficient impress of D_2 is evident to define the hypothetical position of B_2, and a few minor folds approximate this orientation, but obviously this axis is not an axis of appreciable statistical rotation in these rocks. The implication is that B_1 has essentially its original orientation barring gross external rotation of the thrust sheet.

A fold of similar orientation, which was judged well insulated from obvious Alleghanian movement, is the anticline at Cacoosing in structural level B_1 (Figure 54). Geometry of this fold could only be defined by scattered outcrops. Bedding attitudes show a fold with some westward plunge, apparently consistent with its S_1 cleavage, though scatter of the readings leaves some margin of error in defining the precise trend. The limited number of observations makes determination of this axis by β construction practical. The β contours do suggest that there might be

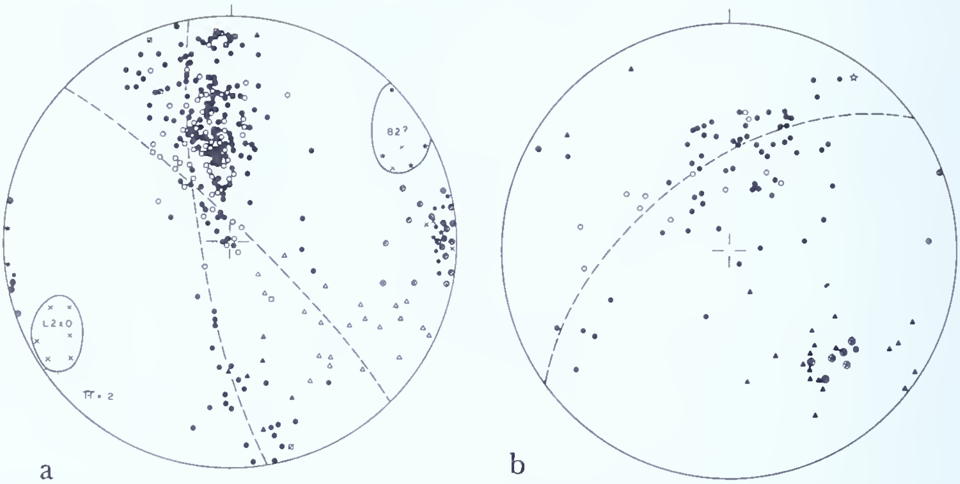

Figure 53. Stereograms of structural elements in structural level D_1, symbols on diagrams listed in Table 2.

a. Areas east of Cacoosing Creek: B_1 fold fabric showing minor development of D_2 and D_3 elements, but no evidence of significant reorientation of older elements.

b. Area west of Cacoosing Creek: Evidence of older folding is essentially obliterated, and fabric for entire area is dominated by D_2' crossfolds, with one minor reoriented (?) normal fold.

a systematic component in the observed dispersion of bedding poles, but effects of D_2 are not represented by deformational elements and the effect is, in any case, slight. These cases serve to show that there are apparently unreoriented B_1 folds indicating a consistent Taconic trend.

Carbonates in the next major anticline to the north barely project into the Sinking Spring quadrangle. With some additional data from the Bernville quadrangle, the stereogram of Figure 55a was prepared. This fold is more asymmetric and may become overturned, but it hardly looks more complex than the preceding example. Its axial orientation is B_2, despite the fact that no clear D_2 elements were noted. Two La lineations observed are consistent with the fold geometry regardless of its age, though La_1 lineation was rarely observed in the level B carbonates. Boudinage (parallel to L_{1xo}) is also present here and not noted elsewhere in level B. Is this then, merely a Taconic fold unusually tight for its structural level with an orientation different from that encountered in previous examples and coincidently parallel to B_2?

Fortunately, shales of the same fold are suited for structural measurements. The stereogram for this area, Figure 55b, shows a fold of identical orientation to that in the carbonate, with the dominant symmetry of fabric clearly related to D_2 elements. Lb_1 lineations are scattered; clearly reflecting reorientation, with a number showing about the same distribution as on the statistical B_2 axis as L_{1x2}. The majority of other Lb_1 readings cluster in the neighborhood of L_{1x3}, which is the same as in the unreoriented folds of the eastern part of structural level D_1 (Figure 53a). These, likewise, probably represent the original B_1 orientation here. The whole character of the fabric is suggestive of strong northwestward shear on S_1. It seems probable, therefore, that the exposed rocks lay not far below the former extension of the Sinking Spring thrust.

The clear implication of both aspects of the fold is complete reorientation of the gross axial trend from an original trend probably close to that observed in the southern anticline of structural level B_1 (Figure 54) and the eastern part of level D_1 (Figure 53a). D_2 movement on the Leinbachs thrust is probable. Such movement would assist in reorienting this adjacent fold.

The author believes the foregoing examples provide a convincing demonstration that bucklefold reorientation of the type studied experimentally by Ghosh and Ramberg (1968) is a real, geologically effective process. Not only minor folds, but also an anticline several miles long, have axes reoriented through a substantial angle to conform with a new stress orientation.

The Hardyston Formation of South Mountain, structural level D_2, on the basis of limited data assembled by the author (Figure 56), shows a fold orientation essentially identical to the Beekmantown Group in the reoriented anticline previously discussed (Figure 55a). The measured fold axis is from a small fold confined to the Hardyston, but the data represent the domain of the major gneiss-cored fold evident in the configuration of the Hardyston basal contact. While the single S_0 reading well removed from the girdle could be some basis for question, most data clearly reflect a kinematically congruent fold system in which only one stage of deformation is apparent. As D_1 effects are evident in Grings Hill (Figure 12) the B_2 orientation of this fold is probably some kind of reorientation effect. However, such reorientation might be the result of external rotation during the D_2 thrusting as well as, or instead of, bucklefold tightening.

The Alleghanian crossfolds (B_2) have already been documented and described in the general description of these features (examples in Figures 45, 46a and 46b). Figure 53b shows that they may be the dominant fold system through a substantial domain. There seems to be three factors which influence the change in structural pattern, between

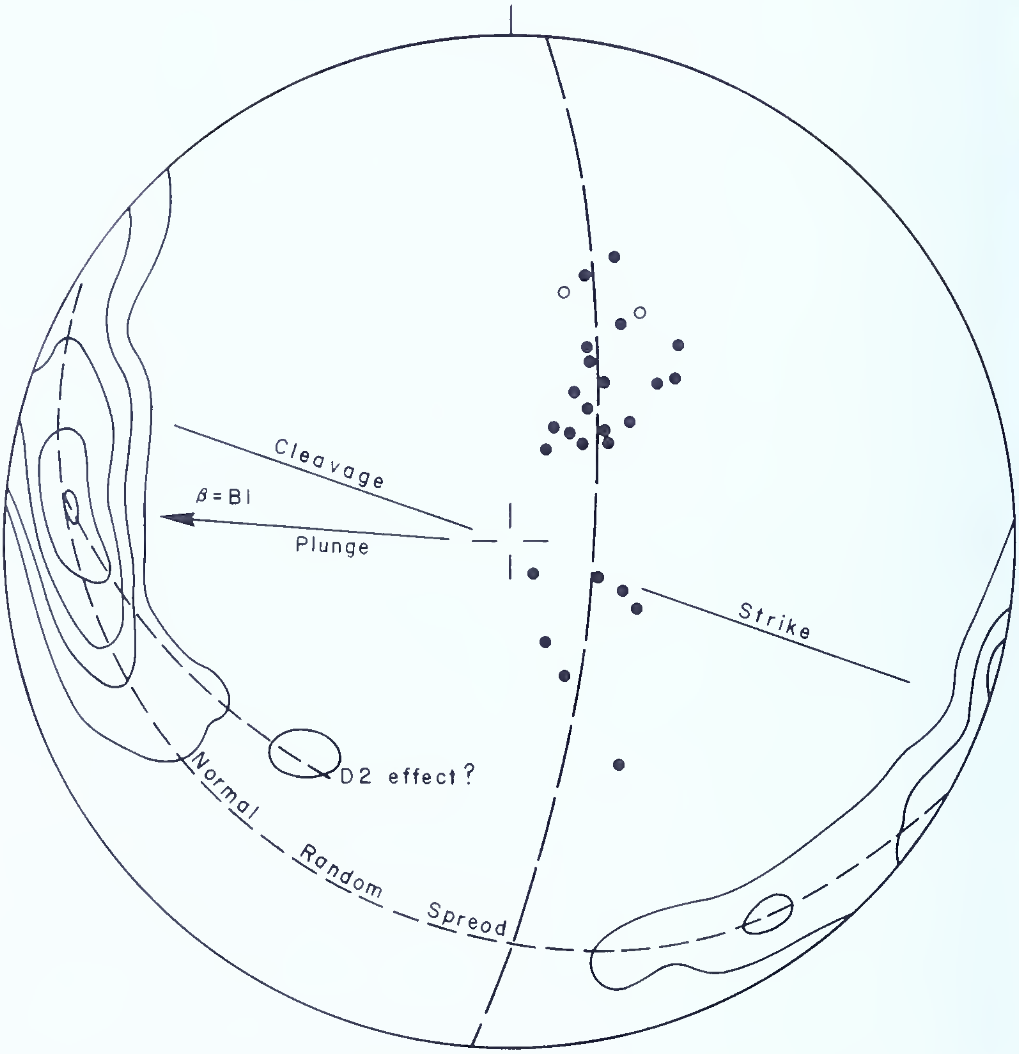

Figure 54. Stereogram domain of anticline in Beekmantown Group in vicinity of Cacoosing, structural level B_1. Maximum density of S_0 poles is normal to obvious girdle in contours of β poles constructed by intersection. This girdle is inherent in the construction and has no significance beyond random dispersion of the bedding measurements from their statistical trend. The β maximum is distinct and clearly defines the plunge of the fold. A subordinate inclined trend in the contours suggests a systematic component in the dispersion of S_0 poles. This would be the product of superimposed deformation, and it is perhaps, more than coincidence that the isolated 2 percent contour lying off the normal random spread lies approximately in the direction of B_2. The trend which seems to be axial trace of mapped digitations is related to cleavage

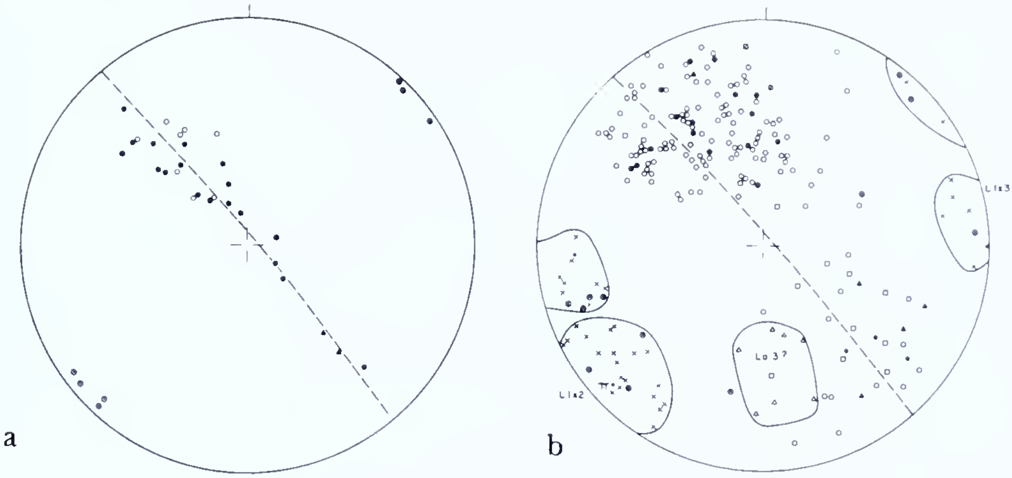

Figure 55. Stereograms of structural elements in northern anticline of structural level B_1.

a. Structure of carbonate rocks. A simple fold with S_1 type cleavage has axis with orientation characteristic of B_2. Minor features in the field suggest greater intensity of deformation than in fold of Figure 55, but measured elements are either in their original position or fully reoriented.

b. Structure of shale. Fold pattern in these structurally sensitive rocks is obviously dominated by D_2 with pronounced folding of S_1. Occurrence of this fabric in same major fold as the above diagram leads to the strong presumption of complete reorientation of the carbonates.

the eastern and western parts of structural level D_1: the plate becomes thinner so that distributed D_2 strain producing the minor D_2 structures to the east is concentrated in a smaller volume of rock; a slice of shale under Grings Hill (level D_2) probably facilitated movement on the thrust, and less stress was frictionally coupled to level D_1 here than under South Mountain, where the shale slice appears to be present only at the western end at the far side of the Womelsdorf quadrangle; the relative sizes of the Grings Hill and South Mountain masses, both anticlinal, suggest that the upper plate was originally thicker in the South Mountain area, putting a much greater load on the thrust. The last factor may well be the most important, but all the above factors work in

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strike; actual trend of axis approximates general trend thought to represent original B_1 orientation through most of the area but may be slightly reoriented by D_2. β contours 2-4-8-16-20%.

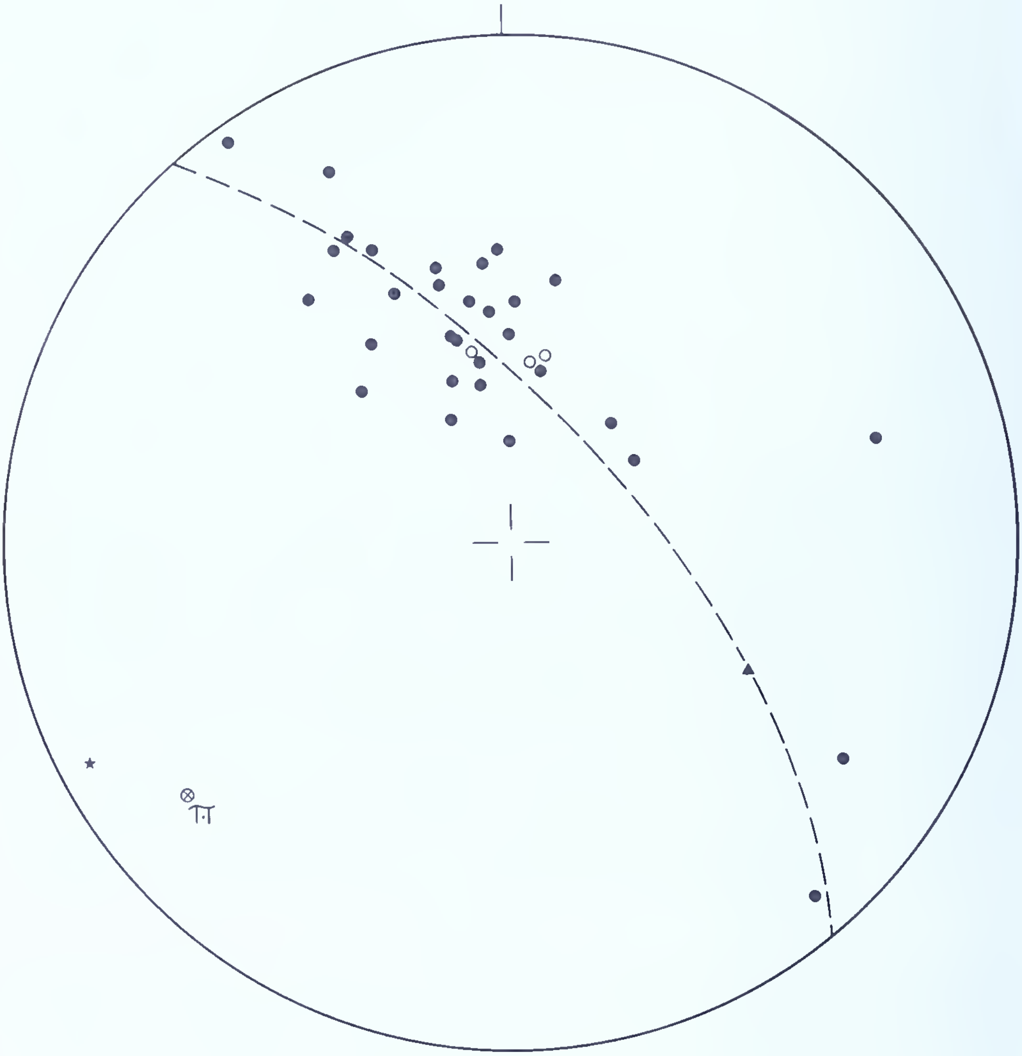

Figure 56. Stereogram of structural elements in Hardyston Formation of South Mountain, structural level D_2. Fabric reflects only overturned folds apparently formed in a single deformation. Axial orientation of folds is parallel to B_2 defined in lower structural levels.

the direction of increasing the strain in level D_1, even if there is no greater transport of the system.

Owing to limitations imposed by rock inhomogeniety, prior deformation, etc., kinematic interpretation solely from the fabric geometry of D_2 in Figure 53 might be questionable. However, by map criteria, simple shear with a large northward component of displacement is known to be a significant feature of the later deformation, D_2. Given this fact, abundant lineation, obviously associated with the transport, clearly specifies its exact azimuth. All other recognized D_2 structural elements are kinematically congruent with the tectonic transport so defined. There is appreciable local variation in attitude of individual measurements; but these variations define a mean, when considered in domains of about one to two square miles, which shows no appreciable variation across the entire quadrangle. Much of the variation is probably the response to mechanical inhomogenieties which are randomly inclined with respect to D_2 movement by D_1. It is also possible that some of the variation is superimposed by D_3 movements larger than can be directly inferred from the D_3 fabric (Figure 51). Any appreciable systematic reorientation of D_2 elements by D_3, however, seems out of the question. It can safely be concluded, therefore, that the N42°W mean azimuth of La_2 is the D_2 tectonic transport direction; and the mean fold axis plunging about 10° S48°W, derived from the statistical concentration of L_{ox2}, L_{1x2}, $B_2{}^1$ and transformed L_{1xo} and B_1, is the kinematically congruent B_2 fold direction.

Taconic Deformation (D_1)

Once the nappe and thrust character of Taconic deformation is recognized, then, as in D_2, large scale subhorizontal transport will dominate structural development. Stratigraphic, paleogeographic, and structural constraints show that the movement is north not south; however, recovering a more precise orientation is complicated by the subsequent deformation. The discussion of fold reorientation in the preceding section provides examples which appear to represent reliable relict Taconic trends, and also examples where initial orientation is less certain.

The approach, in this case, is to pull out the Alleghanian deformation and see what is left. This, of course, is only possible if unreoriented structures remain. This fact seems adequately demonstrated in some favored areas. Even in the areas illustrated in selected examples there is some variation in the inferred D_1 trends, and no basis for assuming that this variation represents the limit. There may well be Taconic folds of initial orientation well within the limits of variation of the various lineations defining B_2. If all folds having B_2 orientation are arbitrarily eliminated, folds validly contributing to the Taconic trend might be lost, and an erroneous trend deduced.

The character of La_1 becomes significant here. The lineation measured in the field is a slip surface lineation, though in some cases it is certainly associated with a penetrative lineation of the microfabric, at least in the lower limb of the Lebanon Valley nappe. As a surface lineation, it is easily obliterated by inclined slip and is unlikely to be found in an appreciably transposed orientation. This conclusion is

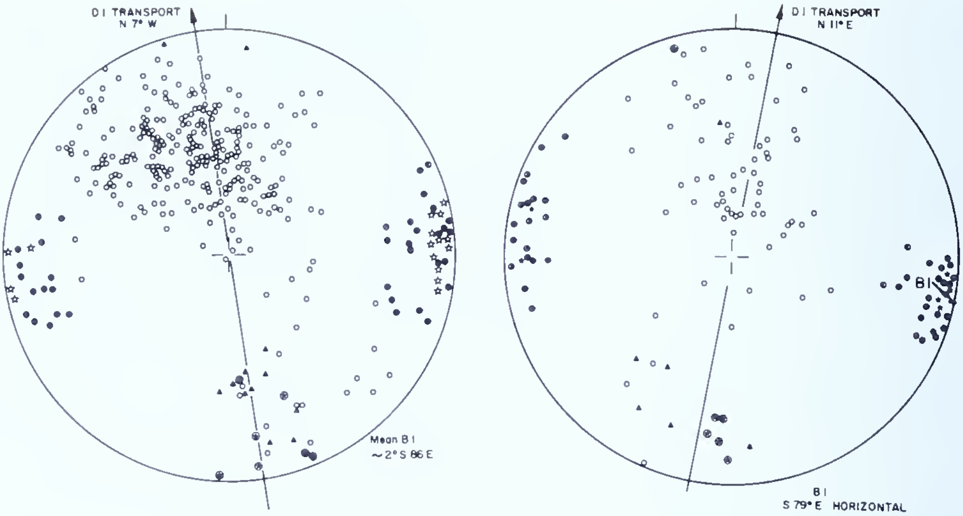

Figure 57. Synoptic diagrams of D_1 fabric elements in Sinking Spring quadrangle. Great variation in S_1 orientation is a reflection of the degree of deformation in the rock by events after cleavage formation. The S_1 girdle defines a regional fold axes B_2^1 in cleavage, consistent with B_2 (Figure 52). La_1 is sentitive to destruction by inclined movements and surviving examples approximate their original orientation. Folds identified as B_1 are residue not falling geometrically in the influence of B_2. (See Plate 3 for details)

a) Fabric of Irish Mountain nappe and associated rocks.

b) D_1 fabric of Lebanon Valley nappe rocks.

validated by field observations which show fairly frequent records of La_1 in folds which were considered substantially unmodified by all criteria, rare examples of La_2 superimposed on La_1 in folds where there is little evidence of modification of the fold though La_2 and sometimes S_2 were noted, and never any lineation considered likely to be La_1 where the fold showed any appreciable evidence of D_2. It is considered probable, therefore, that preserved La_1 does reflect the original azimuth of Taconic movement.

In view of the different stratigraphic provenance of the Irish Mountain and Lebanon Valley nappes, some difference in their direction of movement might be possible. Separate synoptic diagrams were constructed of D_1 elements for the major structural levels. In these diagrams there was no obvious difference in the fabric symmetry orientations for the Irish Mountain nappe elements and the Alleghanian thrust plates of level D which have been consolidated in Figure 57a. Somewhat different orientation is shown in the lower limb of the Lebanon Valley nappe,

Figure 57b. In view of this difference, the similarity of fabric orientations in levels B and D is open to several interpretations. One possibility is that Lebanon Valley upper limb structures of level D were originally parallel to the lower limb structures, but that there was gross external rotation during their Alleghanian advance which fortuitously brought the D_1 trends into the Irish Mountain orientation. It is, however, the local D_1 trend in level C that is, in fact, more anomalous. Lebanon County data have not been geometrically analyzed; but, in Dauphin County, early transport in the Lebanon Valley lower limb was clearly to the west of north and closer to the Irish Mountain trend of this area. The suggestion is that the nappe system as a whole moved generally somewhat to the west of north, and the local movement indicated in the lower limb of the Lebanon Valley nappe is a result of retardation where it overrides the Irish Mountain nappe in this area.

In eliminating D_2 effects there is no choice but to discard all folds and lineations in the neighborhood of B_2. If the residue indicates a mean B_1 kinematically congruent with tectonic transport as implied by La_1, for the reason noted, this procedure may be considered valid. If kinematic congruence is not established, the results are suspect.

Inspection of the diagrams shows that the condition of kinematic congruence of tectonic transport, defined by the mean azimuth of La_1 and the mean B_1, are at least approximately satisfied. In diagram A, there is a three-degree discrepancy between the independently fitted trends which is within the error of the method. In diagram B, the scatter of the few La_1 values recorded is too great for much confidence in a fit within ten degrees or so. In this case, however, B_1 plus Lb define a distinct maximum definitely separated from B_2 rather than grading into the range of B_2. This discrete maximum seems good evidence of the original B_1 orientation in its own right. The indicated tectonic transport direction was, in this case, constructed perpendicular to the mean B_1 axis. It lies well within the range of possible La_1 orientation and is about as good a fit as any in its own right. Some range of error should be allowed in the accuracy of these estimates, but the writer believes the difference between them is sufficient to declare them clearly distinct. It is concluded, therefore, that in the Sinking Spring quadrangle, the Lebanon Valley nappe advanced a little to the northeast and was converging with the Irish Mountain nappe, which advanced a little to the northwest. In both cases, the mean fold axis, B_1, is essentially horizontal and trends a commensurate amount south or north of east. It is clearly these approximately east-west features that dominate the structural grain of the map area, including the average strike of the thrust faults having substantial later displacement inclined to this trend.

Areal Synopsis by Structural Levels

General superposition of four tectonic and stratigraphic terranes in the Sinking Spring quadrangle has already been mentioned in several contexts. Here the relations between the various structural levels and their internal character is summarized in more detail.

For convenience in reference in the following discussion, thrusts which have not been named are designated by a notation derived from the structural levels separated to avoid continued repetition of verbal descriptions. For example, the thrust separating structural level C_{3c} from C_{3d} is designated $C_{3c/d}$, other examples are analogous, i.e. $B_{3/a}$, $C_{1/2}$, etc.

Pelitic Envelope of Taconic Nappes, Structural Level A

North of the Leinbachs thrust, carbonate rocks are apparently present only at appreciable depth and shale deformation seems largely independent of carbonate folds. This area represents a small portion of the level which dominates the area north of the quadrangle. South of the thrust, independent early movement of the shales undoubtedly contributes, but their overall structure is obviously and directly influenced by the deformation in underlying carbonates at the same structural level.

Within the quadrangle, the Hamburg Sequence of level A is predominantly gray shale (lithic type 2) with intercalations of purple shale (lithic type 5) and limestone (lithic type 6) which have discordant contact relations implying syndepositional tectonism. Such features are abundant in the Bernville quadrangle to the north (Myers, 1969, and in preparation). Beds in this area dip generally southward and the facing is uncertain. Indefinite structural indications and the fact that just north of the quadrangle a graywacke siltstone (lithic type 3) dips below these rocks suggests that they are overturned; this is consistent with movement of the Leinbachs thrust. In the Bernville quadrangle, the sequence is internally thrusted but appears generally upright. This is consistent with the position of these rocks in the envelope above the main body of the Irish Mountain nappe. which plunges westward from the vicinity of Reading.

The most conspicuous structural feature of the area is a southeast plunging sigmoidal fold which is apparently related to the nearby transverse fault rather than any of the regional fold systems. The relation between the fault and the fold is most easily explained if the shales were poorly lithified at the time of faulting. The fault, however, is clearly later than, or possibly synchronous with, the Leinbachs thrust; and it has the same strike as faults with definite late or post-Alleghanian movement.

Leinbachs Thrust

This thrust takes its name from the community of Leinbachs in the Bernville quadrangle about two miles eastward along its trace. The Leinbachs thrust probably extends at least 5 miles west-northwestward from the Sinking Spring quadrangle to the vicinity of Host. To the east, it continues its trend nearly to the Schuylkill River. At that point, it evidently turns northward into a tear with steep east dip which again turns eastward into a moderately steep thrust in the vicinity of West Leesport.

Local features along the Leinbachs thrust trace indicate a south dip with moderate up throw of the southern block. In this respect, it is rather similar to the Cacoosing thrust and may have originated at the same time under substantially the same conditions, but questions of age remain. The Cacoosing thrust appears to be truncated by the final emplacement of the Lebanon Valley nappe and therefore is older than at least latest Taconic movements. It is also younger than the early Taconic movements on the Lorah thrust and is thus fairly closely restricted. No data deny initiation of the Leinbachs thrust in the same interval, but the strong impress of D_2 on structural level B_1 would be facilitated by Alleghanian movement. The latter movement, if real, might be only reactivation of the thrust, but there is also no positive evidence that it did not form at this time.

Irish Mountain Nappe, Structural Level B

Between the Leinbachs thrust and the Sinking Spring thrust west to the Hains Church fault, rocks belong to the structural system of the west plunging upper limb of the Irish Mountain nappe. West of the Hains Church fault, a narrower zone is present only north of the Heidleberg thrust, though one or two slices above the Heidleberg thrust were evidently derived from the Irish Mountain nappe but were caught up at the base of the overriding Lebanon Valley nappe.

The exposure within the quadrangle has been divided into sublevels by intersecting thrusts of different orientation and age giving rise to some complication in detail. Possibly a more logical subdivision could be arranged, but the present system does serve to identify individual units under consideration.

Large Taconic folds trending slightly south of west dominate the structure and have been variably affected by Alleghanian deformation.

Structural Level B_1

The Ontelaunee and Epler Formations are exposed in two large anticlines about 2 miles crest to crest. The intervening syncline contains rocks of level B_2. Only the southwestern extremity of the northern carbonate anticline is exposed within the Sinking Spring quadrangle but the same structure is reflected in the shales of the overlying plate. Stereograms of the structures are presented in the analysis of D_2 (Figures 54 and 55). The southern fold is fairly open and has normal Taconic trend. The whole northern fold was reoriented to Alleghanian trend by D_2; appreciable Alleghanian movement on the Leinbachs thrust is implied.

Lorah Thrust

Lorah is a name on older maps for the southern part of the community presently called State Hill which lies close to the best exposures of the thrust. Within the Sinking Spring area the Lorah thrust separates the Beekmantown of the Irish Mountain nappe and shales of the Hamburg sequence. Its age and genesis, consequently its regional extent and significance, are open to more than one interpretation.

The following relationships can be established. It truncates the State Hill thrust and is thus younger than at least part of the stacking of early Taconic thrust or slide slices in the Hamburg klippe. It is in turn cut by the Cacoosing thrust which appears to be older than the final emplacement of the Lebanon Valley nappe. The thrust surface is affected by at least a significant part of the folding in the upper limb of the Irish Mountain nappe and apparently antedates it. Strong tectonic fabric in the best exposure, however, seems directly related to nappe movement and folding

The shale-carbonate contact is a natural surface of structural detachment during the folding, and the thrust was almost surely active at this time, producing the observed fabric. If it originated at this time as a detachment surface, the thrust would presumably stay at about the same horizon with respect to the carbonates and die out northward toward the brow of the nappe. If the thrust is older it could be reactivated, perhaps only more or less locally, depending on the immediate suitability of the antecedent surface for strain relief. In this case, the upper plate should be expected to have some kind of internal consistency, but the position of the thrust could be less regular with respect to the nappe.

As noted in description of the Jacksonburg Formation and the Hamburg sequence, stratigraphic relations could be most simply resolved if the Lorah thrust represented the original sole of the Hamburg klippe. In this case, it would, in places, occur stratigraphically higher and be coextensive with the Hamburg klippe. The writer prefers this interpretation, but the matter is not convincingly resolved. It is possible that both origins are represented in the various areas where the Lorah thrust has been recognized.

Structural Level B_2

This level mostly comprises the rocks of the Hamburg sequence above the Lorah thrust. The exception is south of the Cacoosing thrust where the shale-carbonate relations are the same but the underlying carbonate is referred to as a different level. With respect to the nappe forming and later processes, it appears to be a single unit, but it was formed as a structural composite during development of the Hamburg klippe. The early Taconic State Hill thrust zone essentially emplaces a major slice (level B_2) dominated by shales and graywackes of lithic types 2 and 3 lying in the sixth highest level of the Hamburg sequence recognized by Myers (in preparation) to the north on a major slice exposing purple and green shales of lithic type 5 in the fifth highest slice recognized by Myers. The relationship is locally complicated by inclusion in the thrust zone of a lesser slice (B_{2a}) containing lithic types 3b and 4, the latter appearing at an anomalous position in the structural sequence if it is correctly correlated with greenish, very silty shales characteristic of Myers' fourth level. This slice suggests an additional complication of early thrusting or sliding which cannot be resolved in this area. Lateral relations between the lithic types 3b and 4 is obscure, but the existence of a very early thrust or slide emplacing 3b on 4 and truncated by the State Hill thrust would be simplest in the context of exposures to the north.

Facing of strata in this level north of the State Hill thrust is undetermined, but observed attitudes reflect the form of the anticline in the subjacent carbonates. Thus, at least the later and resolvable deformation is subsequent to emplacement of level B_1 on the Lorah thrust. South of the State Hill thrust strata appear to be generally overturned if the stratigraphic inference that the graywackes are younger than the shales is correct. Sparse local data, mostly of poor quality, tend to support this conclusion by bedding criteria. Such overturning is apparently related to emplacement of the State Hill thrust. Later deformation affecting the Lorah thrust and underlying carbonates probably accounts for the distribution of lithic type 7 quartz conglomerate by preservation in a fold core, but it is not otherwise particularly obvious in the map data of the Hamburg sequence rocks.

Cacoosing Thrust

The Cacoosing thrust appears to the east in the Reading quadrangle where it emerges from beneath the Sinking Spring thrust and extends west to the Hains Church fault where it is evidently overridden by the final emplacement of the lower limb of the Lebanon Valley nappe. It apparently is a fairly steep thrust of moderate displacement generated in the upper limb of the Irish Mountain nappe during its Taconic development. At its west end it splits to define a local sublevel, but the combined movement east of the juncture is sufficient to re-expose the Lorah thrust only locally as it goes down the south limb of the anticline at Cacoosing. A thousand feet of movement up the fault plane would probably be sufficient for this, though uncertainty of the dip prevents precise calculations. Displacement probably increases some to the east within the quadrangle.

Structural Level B_3

The block isolated between the branches of the Cacoosing thrust at its western end is essentially a repetition of level B_{2b} as exposed immediately to the north. Exposure is mostly all buff weathering gray shale (lithic type 2). A zone of graywacke float, with some lithic type 6 limestone fragments in its western part, defines a zone along the main branch of the Cacoosing thrust. This is essentially a repetition of lithic type 3, but the absence of exposure and the somewhat discordant trend of the zone suggest that the rock is brecciated and sliced in on a subordinate thrust in the Cacoosing thrust zone. The area is presumably synclinal in overall character, but the relation between shale stratification and subjacent limestone is obscure. The shale structural fabric shows strong D_2 impress and probably lies not too far below the projected trace of the Sinking Spring thrust. The smaller outliers of the State Hill thrust sheet on the carbonates of the main block of level B_3 have already been mentioned.

There is some possibility that the B_{3a} fault pushed up, with movement dying out eastward to its junction with the Cacoosing fault, during Alleghanian deformation, as the anticline to the south is quite tight relative to the fold at Cacoosing, and is approximately parallel to this fault in a trend suggesting reorientation by D_2. Eastward reduction in movement is suggested by the rather anomalous eastward plunge of the fold which may have been uplifted only at its higher western end to produce this tilt.

The syncline to the south is overturned and almost surely tightened by Alleghanian movement on the Sinking Spring thrust. In the Reading quadrangle the thrust can be observed to override it, and shale is squeezed out into the thrust. Shale observed in the Grings Hill thrust zone (level D_{2a}) is probably of similar origin. The syncline does not appear much reoriented.

Heidleberg Thrust

This thrust takes its name from Heidleberg Township which contains its trace in the Sinking Spring quadrangle. It is the lowest of the series of thrusts developed during emplacement of the Lebanon Valley nappe. Its eastern limit is apparently a tear near the present Hains Church fault, and it extends westward into the Straustown quadrangle where it either joins or is cut off by the thrust underlying the large area underlain by the Hershey Formation which forms the north side of the carbonate valley between Womelsdorf and Lebanon. Exposure is poor in the vicinity of the thrust, but available data from the rock fabrics show no particularly strong impress of Alleghanian elements. In view of substantial Alleghanian movement of the upper limb of the Lebanon Valley nappe and the truncation of the relatively late Taconic Cacoosing thrust, Alleghanian movement on the Heidelberg thrust would not be surprising, but apparently only late Taconic movement of the Lebanon Valley geometry is indicated.

While this thrust is locally the lowest of the Lebanon Valley system, there are strong indications that the immediately overlying rocks are in fact sheared off the Irish Mountain nappe. The displacement of the thrust is accordingly much less than the higher thrust which emplaces rocks actually of the Lebanon Valley sequence.

The Heidleberg thrust rests on structural level B_2 in surface exposure. It is deduced to cut across higher parts of level B at depth and projects out over level A. It is presumed that the nappe movements ultimately died out somewhere in the shale area to the north.

Lower Limb of Lebanon Valley Nappe, Structural Level C

It was noted in the previous section that the structurally lowest rocks participating in Lebanon Valley nappe movement are not strictly part of the main nappe and have been considerably less transported. This is a local phenomenon extending from the Hains Church fault west to the vicinity of Womelsdorf. It is evidently related to the complex slicing apparent in the main body of the nappe above in this area, and it presumably is the result of interference between the Irish Mountain and Lebanon Valley nappes where they overlap. The complex of intersecting thrust sheets makes down dip projections and cross-sections speculative. Section D of Plate 1 is considered reasonable, but other interpretations are possible. It does not seem likely, in any case, that all of this level between the Heidleberg and Sinking Spring thrusts is more than 2000 feet. This represents only a small part of the total thickness exposed in the Lebanon Valley west of South Mountain.

Structural Level C_1

This slice is essentially composed of a substantial overturned syncline cut off above and below by thrusts which are inclined at a low angle to the synclinal axis. Within the quadrangle, the rocks are shaly limestone, apparently passing gradationally upward into calcareous shale. In the Womelsdorf quadrangle (Geyer and others, 1963) rightside-up Beekmantown Group rocks appear in the north limb of the structure. A thrust is shown between the argillaceous limestone and the Beekmantown Group, but they appear to be fundamentally part of the same structural system.

Geometric relations are such that emplacement of these rocks on the Hamburg sequence seems necessarily a consequence of Lebanon Valley nappe movement. Rocks along the south side of the structure are overturned, but the stratigraphy is fundamentally upright and the scale of the folding is that elsewhere, characteristic of upper limb rather than lower limb structures. The structural anomaly is resolved if the fold has been sheared off the upper limb of the Irish Mountain nappe by the overriding Lebanon Valley nappe and incorporated in its sole.

Stratigraphic relations support this conclusion. Argillaceous limestones of the Hershey and Jacksonburg Formations are probably not distinguishable. Inasmuch as the shaly limestone of level C_1 contains none of the Hershey conglomerate which is most abundantly developed in definite Hershey Formation of this immediate area, the conclusion that this rock is to be considered Jacksonburg Formation is probable. Likewise the calcareous shale association is found at least as far west as Evansville in the Irish Mountain nappe and is less prominent in the Lebanon Valley. The occurrence of the Jacksonburg and Martinsburg Formations at this level argues for more than minimum transport of level C_1, however, as these formations are largely absent in the closest exposures of the Irish Mountain nappe. The syncline north of the Sinking Spring thrust in the east presumably projects under the Lebanon Valley nappe, but it is unlikely that the Hamburg sequence exposed in its core would be replaced by the required thickness of autochonous rock in this short distance. The rocks of level C_1 must, therefore, have been derived from at least one fold pair further south, a matter of several miles minimum transport.

St. Daniels Thrust

The south edge of level C_1 is marked by a very poorly exposed belt of noncalcareous gray Martinsburg shale. Map relations require that this contact be faulted, and only a thrust related to the Heidleberg thrust seems plausible in this situation. The thrust has been traced from the

Hains Church fault to St. Daniels Church in the westernmost Womelsdorf quadrangle. It presumably continues westward, but the significance of the distinction between calcareous and noncalcareous Martinsburg shale was not apparent when the Womelsdorf quadrangle was mapped (Geyer and others, 1963).

Structural Level C_2

This slice is predominantly composed of dark-gray, noncalcareous shale of the Bushkill member of the Martinsburg Formation. Locally, at the southern margin, the shale apparently grades down into calcareous shale. The stratigraphic sequence, with a predominance of southward dips, suggests the slice may be generally overturned, but overturning may be limited to the southern margin of the slice. Some graywacke beds occur in the southeast corner, where they have evidently been sliced in by the overlying thrust, but their affinity is obviously to level C_2 rather than level C_3. Scattered exposure suggests fairly complex small-scale folding rather scattered about the Taconic trend; local L_{1x2} was noted.

The rocks of this level appear to be most obviously related to the rocks of level C_1 and are probably derived from much the same portion of the Irish Mountain nappe. The possibility that they are shale, initially autochthonous with respect to the Lebanon Valley sequence and part of the underlimb of the Lebanon Valley nappe proper cannot be excluded by present data. I suspect, but cannot prove, that the shales would be more severely tectonized if they were actually transported far in the sole of the nappe.

Wernersville Thrust

In the Sinking Spring quadrangle this thrust truncates several thrusts which in turn have intersecting relationships which give very complex slicing to the upper plate. The major movement of Lebanon Valley nappe emplacement is probably found here. The structurally highest slice in the plate comes to the Wernersville thrust near the western edge of the quadrangle. This more orderly arrangement persists west almost to Womelsdorf where the fault splits. West of that point, the question of which is a proper extension is uncertain.

Structural Level C_3

This level is a complex of intersecting thrust slices. The highest is interpreted to be the most persistent. The fact that the $C_{3c/d}$ thrust, east of the point where the Sinking Spring thrust overrides level C_{3c}, actually curves around under the Sinking Spring thrust and emerges under the same slice is uncertain. The Epler Formation, assigned to the eastern and western exposures of level C_{3d} as mapped, could, in fact, belong to separate slices intersecting below the Sinking Spring thrust. The western part, in any case, is structurally continuous to the main area of the Beekmantown Group exposure in the Lebanon Valley.

The internal sequence of thrusting is 1) level C_{3d} thrust on level C_{3c}; 2) mutual thrusting of C_{3d} and C_{3c} on level C_{3a}, truncating the $C_{3d/3}$ thrust; 3) in the later thrusting, an apparently overturned slice of the Middle Ontelaunee Formation, level C_{3b}, becomes entrained in the thrust. It is this entire sequence which is cut by the Wernersville thrust.

The overturned C_{3a} slice of the Hershey and Myerstown Formations has typical underlimb structure, as seen in much of the Lebanon Valley nappe. The dip is essentially homoclinal with cleavage approximately parallel to bedding. La_1 lineations run about down the dip. Little other structure can be seen. C_{3b} is nothing but a slice apparently parallel to the bedding and the thrust. Some boudinage is developed in the dolomite beds and plunges at a very low angle almost due east or a little to the south of east, parallel to the Lebanon Valley Taconic B_1 trend.

Level C_{3c} contains the most notable exposure of the Hershey Formation anywhere in the railroad cut at the bridge to the Wernesville State Hospital. The large conglomerate clasts (Figure 19) and all the examples of various superposed structures illustrated from the Hershey Formation in this report are from this cut. Here the shaly limestones dip under the conglomerate; the beds are overturned by stratigraphic criteria. Exposure of this level is poor away from the railway cut, but the Myerstown and Martinsburg Formations associated with the Hershey in this level indicate a fundamentally upright structure with usually prominent folds for the lower limb of the nappe. The structure implies the rocks were derived from the upper limb of a major nappe digitation. Such features are characteristically associated with the leading edge rather than the underlimb of nappe systems, and the occurrence here would tend to support the previous inference that nappe movements die out in the shales to the north. Folds seem to be more sheared out in the overturned rocks close to the sole. The folds plunge gently eastward in the Lebanon Valley Taconic trend but the impress of the Alleghanian deformation is obvious where the rocks are well exposed.

The structure of the Epler Formation in level C_{3d} is fairly typical of the Lebanon Valley type structure in the heavy-bedded carbonates. At the quarry in the southeast corner of Wernersville, the overturned beds are cut by small thrusts, close to the average dip of bedding in the upper plate, in the usual manner of Lebanon Valley thrusts. This is less evident in poorer exposures, but the quarry is representative of the structure believed to prevail throughout the sheet.

Sinking Spring Thrust

The Sinking Spring thrust extends across the quadrangle emplacing rocks of the Conococheague Group in the upper limb of the Lebanon Valley nappe on both the upright Lehigh Valley sequence Beekmantown Group of the Irish Mountain nappe (in structural level B_3), east of the Hains Church fault and on overturned Lebanon Valley sequence Beekmantown of level C_3 in the lower limb of the Lebanon Valley nappe west of the Hains Church fault. West of the Sinking Spring quadrangle it may be overridden by the Grings Hill thrust, the relationship implied by the Womelsdorf map (Geyer and others, 1963); but the writer believes it probably remains just in advance of the latter and brings a slice of the Richland Formation swinging southwestward around the foot of South Mountain as shown on the Tectonic Map (Plate 2). To the east, the thrust cuts down to the crystallines of the Irish Mountain nappe core in the Reading Prong.

Map relations show that emplacement of the upper plate rocks was a late feature though it could be associated with late stage development in the Taconic nappe system. Abundant minor structures showing northwestward displacement on the thrust are the youngest features produced by a major deformational event, and these must be Alleghanian from considerations of regional geology. The Sinking Spring thrust has a low southerly dip at outcrop in the Sinking Spring quadrangle.

At Wyomissing, in the Reading quadrangle, the thrust turns northeastward as it approaches the Reading Prong. At this point it overrides the shale-cored syncline of structural level B_3, and shale is squeezed out of the synclinal core into the thrust plane. This relationship is considered very significant in explaining shale slices exposed in the Grings Hill thrust zone in the Sinking Spring quadrangle and elsewhere.

Alleghanian Thrust Plates, Structural Level D

Rocks of the upper limb of the Lebanon Valley nappe transported an appreciable distance northwestward during Alleghanian deformation are collected as structural level D. The general structural sense of these plates is upright, but there is considerable tightening and overturning of the Taconic folds so that considerable tracts of overturned beds are encountered.

Structural Level D_1

With the exception of the shales in the basal thrust in the Reading quadrangle designated level D_{1a} on the tectonic map (Plate 2), the exposed rock of this structural level is entirely of the Conococheague Group. Exposures within the quadrangle north of the quartzite colluvium are entirely overturned, with the exception of local reversals in relatively small folds. The Richland Formation dips below the Millbach Formation near the southern limit of exposure. In the Reading quadrangle, the Richland again appears south of the Millbach, and it can be established that the exposures in the Sinking Spring quadrangle are on the overturned limb of a substantial anticline in a generally upright stratigraphic section. The band of Millbach Formation mapped under colluvial cover in the Sinking Spring quadrangle is obviously an oversimplification, but it is believed to be an accurate approximation. The width of the Millbach exposed in the anticlinal core varies very little from the first exposure of the southern contact below a thrust, near the Schuylkill River, westward to the quadrangle boundary. Structural data from exposures in the limb of this structure in the eastern third of the Sinking Spring quadrangle (Figure 53a) confirm low plunge, so the uniform width of the Millbach belt should persist through this domain. What happens to the Millbach Formation as it approaches the Grings Hill thrust and gets involved in the domain of NW-SE trending B_2 cross-folds associated with the thrusting of the South Mountain mass is very uncertain.

Grings Hill Thrust

The Grings Hill thrust basically lies below the Precambrian rocks and Hardyston Formation of South Mountain and Grings Hill. Across most of the quadrangle these rocks rest directly on level D_1 with a thin slice of shale (D_{2a}) locally included in the vicinity of Grings Hill. Near the eastern edge of the quadrangle the thrust either splits or a distinct thrust is overridden, introducing a slice of the Buffalo Springs Formation between levels D_1 and D_2. This is a minor feature of the Sinking Spring quadrangle, and has been given the subordinate designation D_{2b}. It is a major level in its own right in the Reading quadrangle. Somewhat comparable relations may also pertain on the west end of South Mountain in the Womelsdorf quadrangle. Movement on the thrust is large but indefinite. A minimum of several miles would seem to be indicated by projecting down the dip of the cross sections and reconstructing the probable closest locus of suitable lithology in the lower plate.

Shale included in the thrust surface, designated as structural level D_{2a} on the Tectonic Map (Plate 2), was probably introduced in a manner similar to that described along the eastern part of the Sinking Spring thrust. It is of particular significance because the recurrence of this structural level south of the diabase sheet in the Womelsdorf area places severe constraints on structural interpretation of the border of the Triassic basin.

Structural Level D_2

Within the quadrangle, the upper plate of the Grings Hill thrust is composed entirely of the Hardyston Formation and Precambrian rocks which are described elsewhere in this report. Problems relating to Paleozoic fold structure in these rocks are mentioned in discussion of Alleghanian (D_2) deformation.

GEOLOGY OF THE TRIASSIC BASIN

by Dean B. McLaughlin and David B. MacLachlan

STRATIGRAPHY

Newark Group

General statement

The Newark Group comprises the entire body of a thick sequence of upper Triassic sediments which fill the Newark-Gettysburg basin. This major structural feature extends through, or is marginal to, the crystalline Piedmont from the Hudson to the Potomac Rivers. Exposed basal portions of this sequence are commonly arkosic and appear to have been derived from crystalline rocks of the Piedmont more or less immediately adjacent to the south or southeast. In the Gettysburg portion of the basin, these rocks are called the New Oxford Formation, and this name is carried eastward most of the way south of the Sinking Spring quadrangle to the vicinity of Terre Hill. In this area, typical rocks are interrupted by a local conglomerate zone. Eastward from this conglomerate the New Jersey name, Stockton Formation, is used for substantially identical rocks.

Overlying the basal arkosic formations are thousands of feet of predominantly fluviatile rocks which grade into paludal and lacustrine deposits in areas most remóte from the detrital sources. The petrography and depositional structure of these rocks indicate they were formed of detritus from Paleozoic sediments to the north and northwest. The geometry of present exposures is such that paludal and lacustrine deposits are now exposed only in the lower part of this sequence, but the former existence of such deposits, as eroded lateral equivalents of younger strata, cannot be precluded. Throughout most of the basin, the fluviatile beds are predominantly red silts and shales with subordinate sandstones. To the east, these rocks are referred to as the Brunswick Formation, with lacustrine and paludal deposits designated Lockatong Formation. To the west, they are called Gettysburg Formation. This name has been used for rocks west of the Little Muddy Creek fault in the Sinking Spring quadrangle (Gray, Shepps, and others 1961; Geyer and others 1963). In Berks, Lebanon and northeastern Lancaster Counties, however, the upper Newark Group rocks are much coarser grained, with sandstone and conglomerate the predominant lithic types. This coarse facies has been designated the Hammer Creek Formation by Glaeser (1963) and represents the distributary deposits of a major stream system entering the basin from the north. Sedimentalogical studies (Glaeser, 1966) show that this system was the major source of basin fill.

Conglomerates of the Hammer Creek Formation are fully described in the next section, but certain distinctive features may be noted here. These conglomerates are commonly well sorted with a clean, shale-free matrix. The coarse clasts are rounded and predominantly of lithologies which do not now appear immediately adjacent to the locus of deposition. In general, conglomerate apears to be increasingly more abundant higher in the section, except possibly the uppermost part, but conglomerate beds are present throughout the entire thickness of the Hammer Creek Formation. These characteristics are clearly distinct from those of irregular lobate conglomerate masses which appear along much of the northwestern margin of the Newark-Gettysburg Basin.

The local conglomerate masses are poorly sorted with abundant shaly matrix. The clasts are commonly angular and usually reflect the lithology of immediately adjacent exposures of pre-Triassic rocks. Conglomerates of this type are a strictly marginal facies, which is an important link in the evidence establishing that the northwestern depositional limit of the Newark Group approximates the present limit of exposure. These conglomerates evidently represent local alluvial fans, mudflow deposits, and possibly even talus, but these local sources were only a minor component in the basin fill (Glaeser, 1966). Local relief at the depositional margin of the Triassic basin was evidently reduced in the western Berks—Lebanon County area, where the major stream system (ancestoral Schuylkill?) entered from the north. Locally derived conglomerate is correspondingly rarer in this area. Occasional locally derived elements have been observed in the Hammer Creek Formation in the Sinking Spring quadrangle, and they are noted in the lithic description.

Hammer Creek Formation

The Hammer Creek Formation (Glaeser, 1963) consists of red, brown, and gray sandstone, fine to coarse quartz conglomerate, and some red shale, all of which are interbedded to some extent. Locally, limestone conglomerate is found. Conglomerates are dominant in Laurel Ridge, in the hills southeast of Fritztown, and in the southeastern corner of the quadrangle, and they form an important fraction of the rock in the hills about Camp Indiandale. Elsewhere, sandstone, siltstone, and shale form the greater percentage of the rock.

Gettysburg Formation type red shale, typically non-micaceous, is interbedded nearly everywhere with siltstone and sandstone. The shale is thin to medium-bedded, usually friable, never fissile, and has a hackly fracture. Thin-bedded varieties usually have wavy or uneven bedding. Ripple marks and mudcracks are present. The shale is so easily eroded that it is not often seen in outcrop, and in no case is it the major component of an exposure. Only in deep cuts, such as the railroad cut near Vinemont, is it seen well exposed.

Sandstone is the most common rock type of the Hammer Creek and is the dominant type in much of this area. The sandstones range in color from red through brown to light gray; brown sandstones are the most common. In some places, in this and adjacent areas, nearly white sandstones are encountered. The writer believes that hematite, which is a common colorant of Newark sediments, has been leached from some of these white sandstones, especially those on the crests of some hills. However, a very persistent, thick, "white sandstone" member along the south slope of the Furnace Hills in the Lititz and Manheim quadrangles may have been originally without appreciable hematite.

Sandstone bedding thickness ranges from one or two inches to a foot or more. Cross-bedding, lensing, and channeling are common (Figure 58). Ripple marks occur in some of the finer sandstone beds. Grain sizes range from very fine to coarse; in general, the thin-bedded varieties tend to be fine grained. The finer sandstones and siltstones are well sorted, but coarser varieties are usually rather poorly sorted.

Hammer Creek sandstone is composed principally of angular to subround, colorless quartz grains and a small percentage of miscellaneous rock fragments imbedded in a matrix of clay-size material with hematite. The sandstones grade, on the one hand, into siltstones with a high percentage of matrix, and on the other into conglomerates. The Hammer Creek sandstones are rarely feldspathic. In this area, however, there are apparently two horizons of rather feldspathic and micaeous sandstones east and northeast of Reinholds. One belt extends for several hundred yards along the Fritztown Road about one-half mile east of Reinholds, occurring as float in the fields both north and south of the road. A second belt lies on the northwest slope of the hill north of the Fritztown Road, about one-half mile northeast of Reinholds. The most likely source of

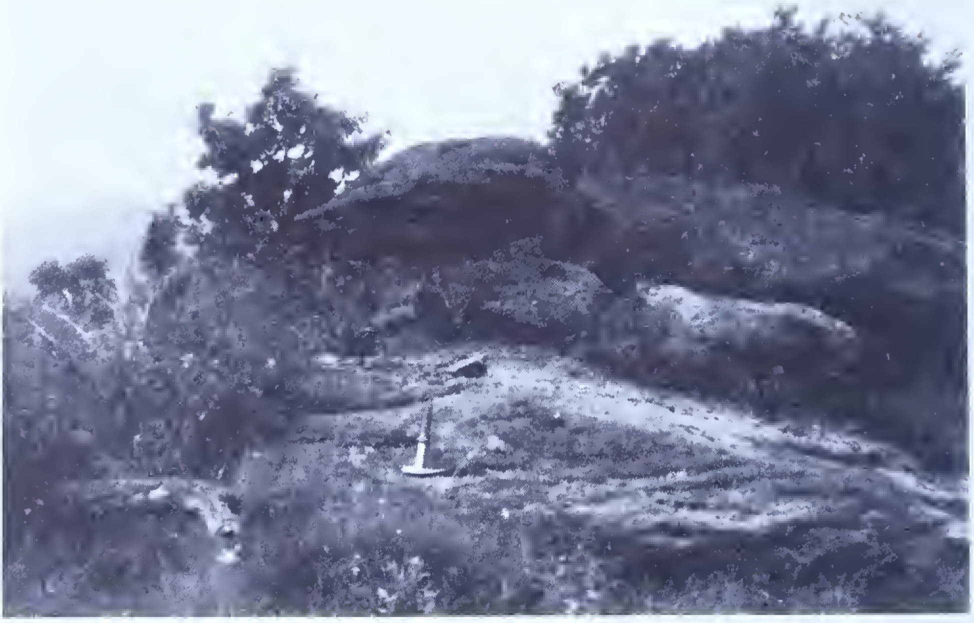

Figure 58. Cross-bedded Hammer Creek Formation sandstone along power line near Camp Indiandale (Vinemont vicinity).

feldspar and mica in this area is probably the feldspathic and schistose facies of the Hardyston quartzite that occurs immediately to the north of the Newark basin.

Another type of sandstone that deserves special mention occurs in the area about Camp Indiandale. There are numerous small pits in the wooded hills of the area, from which the rock has been quarried, either from outcrops or from enormous boulders. The rock is a thick-bedded to massive brown sandstone of the type often called "brownstone", with a remarkably uniform medium grain throughout. It closely resembles the Hummelstown brownstone. There are no very large exposures. It forms a considerable part of the sandstone member between the conglomerates designated I and II in the Indiandale section (see Figure 62).

Coarse quartz conglomerates form some prominent ridges, notably Laurel Ridge (Figure 59), and nearly all of the higher hills within the area of Newark rocks. The hilly area in the southeastern corner of the quadrangle is entirely underlain by coarse cobble conglomerate with only minor thicknesses of sandstones. Conglomerates are prominent in the steep wooded hills about Camp Indiandale.

The conglomerate is typically thick-bedded and occasionally is so massive that bedding is difficult to recognize in small exposures. Almost everywhere minor sandstone interbeds occur. Pebbles and cobbles of quartz, quartzite, and sandstone are densely to sparsely distributed in bands and lenses from one or two inches up to many feet in thickness. Cobbles up to 5 or 6 inches in diameter occur in some of the thickest beds. In the area south of Gouglersville, occasional cobbles are 9 to 10 inches in diameter. Bands and lenses of large cobbles or pebbles alternate with beds containing smaller pebbles, or with beds of sandstone with just a sprinkling of pebbles. The conglomerates grade into pebbly sandstone with decrease in the dimensions and number of pebbles.

Occasionally, pebbles and cobbles in these conglomerates are nearly touching, with groundmass filling only the interstices. More commonly, groundmass forms more than 50 percent of the rock. The groundmass of the conglomerate is similar in composition to the coarser sandstones. It consists chiefly of angular to subangular grains of quartz, tiny fragments of quartzite, and occasionally fine sandstone and other rock fragments, all of which are bound together by a matrix of clay-size material, usually with some hematite present. Some white to gray conglomerates appear to be cemented by silica and to a minor extent by calcite.

A major percentage of the large pebbles and cobbles in the Hammer Creek Formation conglomerates (Figure 60) of this area are light-gray, fine- to medium-grained quartzite. On the evidence of close lithologic resemblance, these types are identified with Silurian Tuscarora quartzite

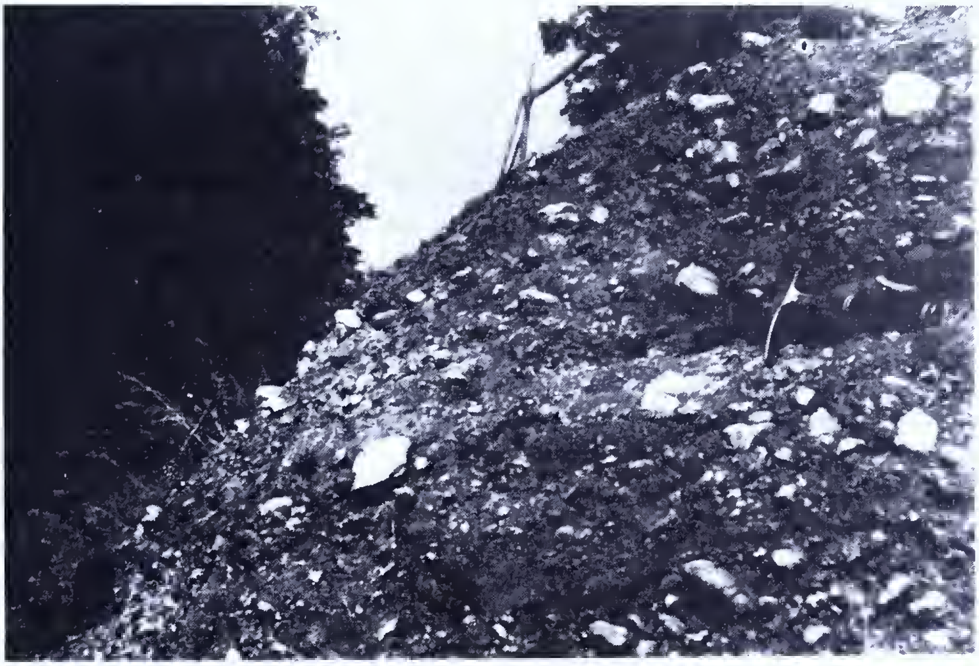

Figure 59. Hammer Creek conglomerate on Laurel Ridge west of Fritztown.

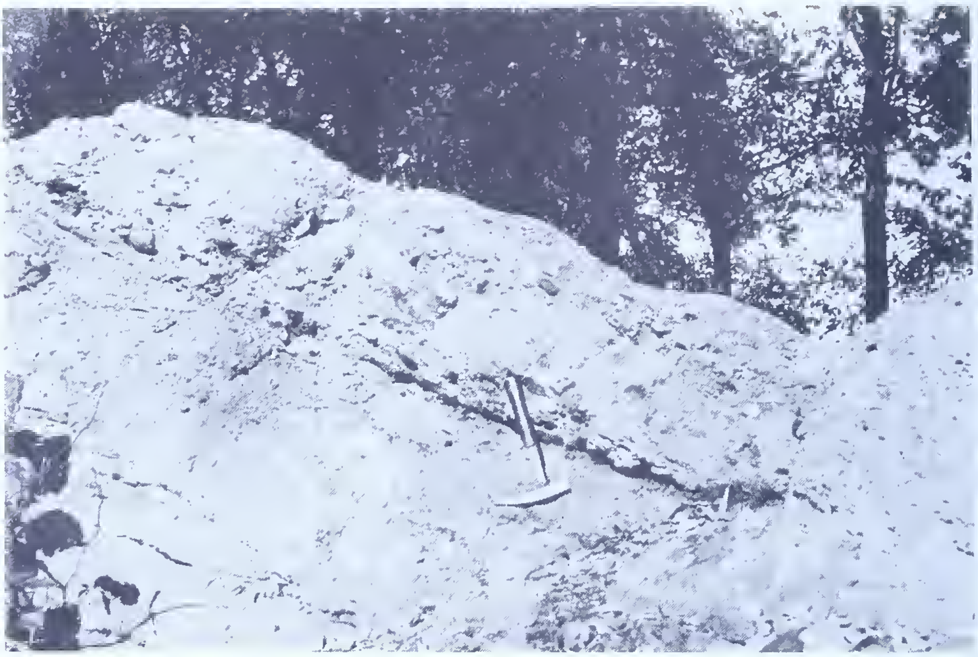

Figure 60. Hammer Creek conglomerate on Reinholds Ridge.

which is exposed about 15 miles north of the Triassic north border. A scattering of brownish and reddish brown, fine-grained sandstone pebbles may have been derived from Silurian Clinton or Bloomsburg Formations. A large percentage of the smaller pebbles are of vein quartz, colorless, white or pink.

In the Womelsdorf and Richland quadrangles to the west, considerable areas of shale conglomerate were mapped. In the Sinking Spring quadrangle no mappable bodies of this type occur. Locally a few chips of probable Martinsburg shale have been found in the conglomerates of this area, notably east and southwest of Gouglersville. Only a very small area of Martinsburg shale adjoins the Newark rocks of this quadrangle. It is noteworthy that all the areas of shale conglomerate west of here lie close to, or actually adjoin, areas of Martinsburg shale immediately north of the Triassic belt.

Considerable numbers of limestone pebbles occur in the conglomerates at two places. One is in the road cut of U. S. Route 222 about 0.4 miles west of Gouglersville (Figure 61). There, on the south side, the conglomerate contains mixed quartzite and limestone pebbles, and on the north side a bed about two feet thick contains almost exclusively limestone pebbles up to more than two inches in diameter. The other locality is an exposure along the railroad about 200 yards south of Fritztown, where quartzite and limestone pebbles occur in a rather chaotic conglomerate.

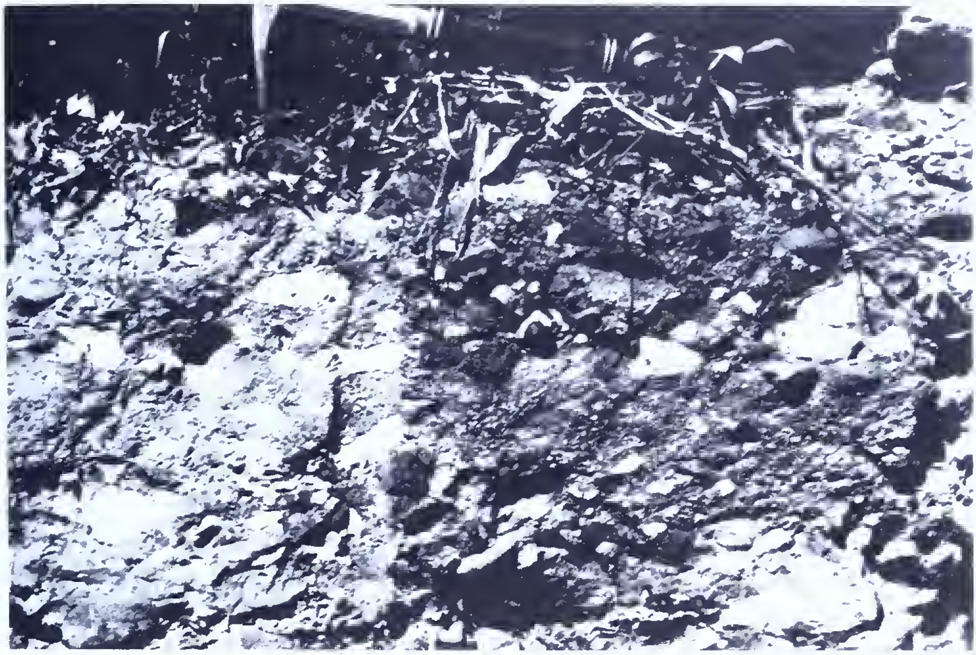

Figure 61. Limestone conglomerate on U.S. Route 222 near Gouglersville.

This conglomerate contains typical quartzite clasts (Tuscarora?) and some reddish sandstone clasts (Clinton – Bloomsburg?) up to about 6 inches, and limestone clasts up to 10 inches. The rock shows only very crude bedding and has the appearance of having accumulated near the foot of a steep slope, with only a little reworking by the action of water. It points to the conclusion that the border in Newark time was very nearly in the same position that we now find it near Fritztown. At several places within one or two miles of the north border, some beds were found to contain angular cavities that looked as if limestone pebbles had been dissolved out. If this interpretation is correct, limestone conglomerate may be fairly widespread in the area, but the susceptibility of the pebbles to removal by solution makes detection unlikely.

One other occurrence of limestone "conglomerate" is problematical. This is an apparent breccia of limestone fragments in a limestone matrix that overlies apparently solid limestone in the easternmost pit at the old Wheatfield Mines east of Fritztown. The rock is intensely metamorphosed by a diabase intrusion. It is possible that this material is a tectonic breccia, but the writer considers it more probable that it is a conglomerate at an unconformable contact of the Newark rocks upon the Paleozoic limestone.

Limestone conglomerate is greatly developed in the neighboring Reading quadrangle, along the Schuylkill south and southeast of Reading.

The nearest part of the area is only about six miles from the Gouglersville occurrence of limestone conglomerate and lies roughly along strike of the latter. However, interruption of continuity by a thick body of diabase, as well as local warping and reversals of dip near the north border, render a correlation uncertain.

Although Hardyston quartzite and Precambrian gneisses now adjoin the Newark rocks across nearly the entire width of the quadrangle, no undoubted Hardyston or Precambrian pebbles have been found in the Hammer Creek conglomerates of this area. On the telephone line on Laurel Ridge, about 200 yards west of Vinemont Road, an outcrop shows many chips of schistose, very fine-grained, light gray quartzite of uncertain affinity. Possibly they were derived from a schistose facies of the Hardyston, but it seems possible they are from sheared Tuscarora that may have been exposed in the north border fault zone in Newark time. In the Womelsdorf quadrangle, numerous pebbles of highly vitreous Hardyston quartzite occur in some of the conglomerates, but all the beds in question are in the uppermost part of the Gettysburg column, and none of them extend into the Sinking Spring quadrangle. From the evidence in the Womelsdorf quadrangle, it was concluded that the Precambrian rocks of South Mountain were not unroofed until after the close of Newark sedimentation.

Columnar sections. No single, well-exposed, thick stratigraphic section occurs in the Sinking Spring quadrangle, though sections of a limited thickness of strata are found in the vicinity of Camp Indiandale and in the railroad cut near Vinemont. To the west, in the Richland quadrangle, the section along Hammer Creek is 9,400 feet thick (Locality 5 of Appendix). In the same quadrangle, a north-south section along Segloch Run, across the entire width of the Hammer Creek Formation to the north border at Schaefferstown, gives a computed thickness of 12,200 feet. The same conglomerate and sandstone units that occur in the Richland quadrangle have been traced into and part way across Womelsdorf quadrangle. Several thousand feet of the highest beds terminate against the north border fault in the Womelsdorf quadrangle and are missing in the Sinking Spring quadrangle. The lower part of the section continues into the Sinking Spring quadrangle. An independent calculation, based entirely on evidence from Sinking Spring and Terre Hill quadrangles south of it, gives a total thickness of about 10,000 feet for the Hammer Creek formation in this area.

Columnar sections have been calculated for limited thickness of strata at two localities. One is the area about Camp Indiandale; the other is in the railroad cut near Vinemont.

Four partial sections were calculated in the Camp Indiandale area. Two of these are indicated as A-B and C-D in the sketch map, Figure 62. A third extends due eastward from Indiandale Road along the axis of the plunging syncline. A fourth is along Indiandale Road on the north limb of the complementary anticline. None of these sections afford a continuous exposure, but outcrops and residual boulders are very abundant. The four sections, and an adapted section based on the figures that are judged most reliable, are tabulated below.

Table 3. *Sections near Camp Indiandale*

	Sec. A-B	Sec. C-D	Axis	N. limb	Adopted
Coarse conglomerate (III) with quartzite cobbles	277 ft.		197 ft.	188 ft.	225 ft.
Medium-grained brown and gray sandstone	168		190	150	170
Coarse conglomerate (II)	270	328 ft.	390	242	300
Medium-grained brown sandstone		248	282	229	250
Coarse conglomerate (I)		311	350	200	310

The railroad cut northeast of the former Vinemont Station (Locality 4 of Appendix) affords a nearly continuous exposure of a thick series of sandstone and shale between two conglomerate members. The base of this section is estimated to be 200 to 300 feet stratigraphically above the top of conglomerate member III of the Indiandale section.

Uncertainty of precise correlation across the Little Muddy Creek fault produces corresponding uncertainty as to the total thickness of the Hammer Creek Formation in this quadrangle, since the beds that appear to be stratigraphically highest are the sandstones in the diabase-rimmed area east of Fritztown, east of the fault, while the most reliable section from the base of the Gettysburg up to the prominent conglomerate, is west of the fault. Thus, for the sandstones from the base of the formation near the crossing of the Turnpike and U. S. 222 in the Terre Hill quadrangle up to the base of conglomerate I, a thickness of about 4,000 feet is calculated. To this is added the Indiandale section, 1,255 feet, and 2,300 feet of sandstone and cobble conglomerate above it to the north border, giving a total for the Gettysburg Formation west of the fault of 7,555 feet. If we assume that the highest conglomerates near Fritztown are equivalent to the uppermost conglomerates one-half mile north of Gouglersville, then we must add the thickness of sandstone in the diabase-rimmed area, about 2,400 feet. This brings the total stratigraphic thickness of the Hammer Creek Formation in the Sinking Spring-Terre Hill area to 9,955 feet, but it may well be at least some hundreds of feet greater.

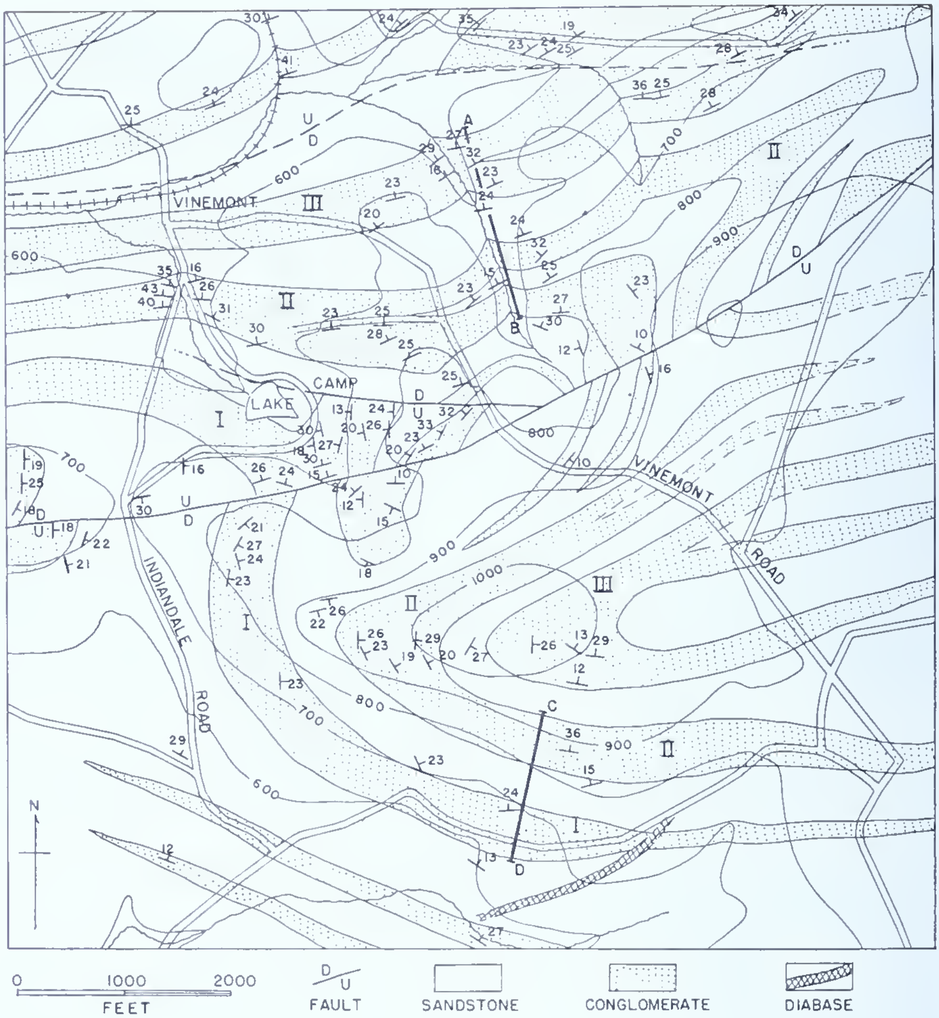

Figure 62. Geologic map of an area one to two miles south of Fritztown, in Sinking Spring quadrangle, Berks County, Pennsylvania. Contour interval 100 feet. Conglomerate members are designated by Roman numerals I, II, and III. Locations of sections measured are indicated by the lines A-B and C-D.

Hammer Creek sedimentation. Glaeser (1966) has shown, on a regional basis, that the major part of the Gettysburg-Hammer Creek-Brunswick sediment was introduced across the north margin of the basin in the western Berks-Lebanon County area and transported longitudinally eastward and westward. In the area of sediment input, the result is a complex of lensing and tonguing conglomerate bodies, which evidently represent deposits of shifting distributaries in a major stream system. There was evidently an appreciable change in gradient at the depositional basin margin, which approximates its present locus, with resulting construction of an alluvial fan complex. Effects of shifting distributaries of the major stream and more local contributions from less enduring minor streams cannot be clearly separated; but the site of maximum conglomerate deposition changes a number of times during Hammer Creek time, and a number of apparently separated conglomerate bodies appear to be contemporaneous.

Streams depositing Hammer Creek sediments in the Sinking Spring quadrangle, for the most part, entered the basin within the limits of this quadrangle and east of it. Little or no sediment came from the west. This is shown by the rapid fingering out and disappearance of conglomerates westward, which continues into the Womelsdorf quadrangle. Crossbedding attitudes support this interpretation.

The large area of conglomerate in the southeastern corner south of Gouglersville contains particularly coarse cobbles. The source was probably to the northeast in the Reading quadrangle, for very coarse conglomerate extends eastward entirely across the Reading quadrangle and into the Birdsboro quadrangle east of it.

The conglomerate on Laurel Ridge and east of there to Bran Road is considered to be the stratigraphic equivalent of a part of the conglomerate mass in the southeastern corner. While all of the Laurel Ridge conglomerate is coarse, the cobbles do not attain the extreme dimensions found in the southeastern area. It is concluded that Laurel Ridge is simply the western extension of the same alluvial fan that is represented by the southeastern conglomerates and their extension into the Reading and Birdsboro quadrangles. However, smaller fans with apexes north of the present outcrop from Laurel Ridge to Fritztown may have contributed to the formation of these conglomerate masses.

The conglomerates in the Camp Indiandale area show rather rapid fingering out both eastward and westward. Stratigraphically, they are considerably lower than Laurel Ridge. They are belived to have been deposited by a stream that entered the basin almost centrally in the Sinking Spring quadrangle.

Within a radius of a mile about Camp Indiandale, 57 observations of crossbedding indicated streams flowing variously from north, west, and east, but predominantly from the northeast and east. The distribution of these directions to source is indicated in Table 4. Several of the indications of a western source were noted in the same outcrops in which other crossbeds showed an eastern source. This points to deposition by shifting distributaries.

In the extreme southwestern corner of the Sinking Spring quadrangle, the lowest conglomerates probably represent fingering out of thicker and coarser conglomerates from farther west in the Womelsdorf quadrangle.

Table 4. *Inferred Source Directions near Camp Indiandale, Based on Observations of Crossbedding*

Direction to source	West of Camp	Near Camp	East of Camp	All Measures
South	0	1	0	1
Southeast	0	1	0	1
East	3	9	7	19
Northeast	3	3	8	14
North	0	6	1	7
Northwest	0	2	2	4
West	3	6	1	10
Southwest	0	1	0	1

None of these are perfectly continuous in outcrop with the main conglomerate bodies of Furnace Hills. Rather, they seem to represent the outer fringes of a fan deposited by a stream that entered the basin a few miles west of the Sinking Spring quadrangle. Its contribution to the total of Hammer Creek sediments in this area was relatively minor. This is the only evident exception to the conclusion that most of the sediments in the quadrangle were deposited by streams that entered the basin within the borders of the quadrangle or to the east of it.

As compared to the local fan deposits at the northwest margin of the Gettysburg and Brunswick terranes, which closely reflect immediately adjacent pre-Triassic lithology, the stream system transporting the bulk of the Hammer Creek sediment may be reasonably supposed to be competent to transport coarse detritus a somewhat greater distance. The discrepancy in composition between the Hammer Creek conglomerate clasts and adjacent pre-Triassic rocks, nevertheless merits some consideration. The bordering rock now is Hardyston quartzite for most of the distance across the quadrangle. At the Wheatfield Mines, east of Fritztown, the Triassic rocks are bordered by limestone and little Martinsburg shale, and for a little more than a mile near the western edge of the quadrangle, gneiss adjoins the Triassic north of Laurel Ridge. While occasional exposure of limestone and shale clasts have been previously noted, the quartzite and gneiss predominantly exposed in this area are not represented by conglomerate pebbles. Only minor local feldspathic sand bodies seem to reflect this provenance.

The absence of Hardyston and Precambrian, and the low abundance of Lower Paleozoic pebbles generally admits two possibilities. Either the older rocks were mostly still covered at the time of Hammer Creek deposition, or these rocks formed terranes of sufficiently low relief that they contributed little coarse detritus. The latter situation appears to have applied where Hammer Creek rocks uncomformably overlap Paleozoic limestones southwest of Schafferstown in the Richland quadrangle. It seems less likely in areas adjoining the Hardyston Formation, which would probably be erosionally resistant in almost any climate; though it might be argued that it is possible where the belt of resistant rock lies athwart the lower reaches of a substantial stream system, as is implied in this area. On the other hand, the chaotic conglomerate south of Friztown, previously described, indicated steep slopes were at least locally present without yielding Hardyston quartzite or gneiss debris. It follows that when the Newark rocks were deposited, Tuscarora quartzite was exposed nearby and South Mountain must have been almost wholly covered by Ordovician and Silurian rocks. The streams flowed, for the most part, over Tuscarora and younger rocks. In some places (as attested by a sprinkling of shale flakes) they had eroded down into Martinsburg shale, and the occasional small patches of limestone conglomerate show that the limestones below the Martinsburg were being eroded locally. Even when the existing record ended, the streams probably had not yet eroded down into the Hardyston Formation within this quadrangle. Farther west, in the Womelsdorf and Richland quadrangles, where the uppermost Newark rocks are younger than any in the Sinking Spring quadrangle, we do find considerable amounts of Hardyston and Martinsburg material in the upper conglomerates. Only a thin band of limestone conglomerate occurs at the unconformable contact of Newark rocks upon limestone at the north border near Schaefferstown, which evidently reflects relatively low relief on the limestone surface in this area of overlap. The conglomerate petrography, therefore, points to the existence of a major fault at the north border, which has brought the Newark sediments into juxtaposition with the present South Mountain rocks only after the end of the period of sedimentation.

Igneous rocks: Diabase

The southeastern part of the quadrangle is intruded by a thick diabase sheet which is cut on the west by the Little Muddy Creek fault. This sheet extends about 20 miles south eastward into Chester County and takes the name Morgantown sheet from exposures of its south limb in that vicinity. The sheet lies mainly in Newark series rocks, though it locally encroaches into older rocks in the Wheatfield Road vicinity of this quadrangle and again to the south in the Morgantown area.

Several narrow diabase dikes of no great extent cut the Hammer Creek Formation. Regionally, such dikes are quite abundant in the Triassic rocks, and less so in older rocks adjacent to the basin; some extend for many miles. In this respect, the Sinking Spring quadrangle seems to be somewhat anomalous, as dike development is more pronounced in pre-Triassic rocks to the north. Age relations between the dike and sheet intrusions cannot be established in this area, but on theoretical grounds, the dikes are considered to be generally somewhat younger than the sheets in Pennsylvania.

Exposure conditions make documentation of this relationship difficult here, but it has been definitely established in the very similar sheet and dike complex of the Karroo dolerites in South Africa (Walker and Poldervaart, 1949).

Two dikes have small podlike masses associated with them on the same trend. These reach maximum dimensions of about 800 by 200 feet as deduced from surface debris. They have no aeromagnetic expression and do not appear to be parts of larger bodies. They are presumed to be related to dike formation, possibly forming in intensely fractured zones in the intruded rock. Somewhat comparable bodies in the carbonates are directly connected with dikes.

The diabase of the major intrusion is a medium- to coarse-grained, dark gray rock with ophitic texture, composed chiefly of gray plagioclase feldspar and black or greenish-black pyroxene. The coarsest varieties are the more conspicuously feldspathic and are lighter in color. The outer zones of the large intrusions, and the entire mass of the narrow dikes, are fine-grained, much darker gray to black, and apparently less feldspathic. Next to the sediments, the grain of the chilled contact facies may be invisible to the naked eye, and the rock may superficially resemble the adjacent tough, black hornfels. The rock in outcrop is very massive and weathers into large spheroidal boulders that cover wide areas. Such land is unfit for cultivation and is usually heavily wooded. Where the rock is more thoroughly decayed, a bright orange-brown clayey soil results from oxidation of the iron minerals and decomposition of the feldspar. Excavations where the rock is deeply weathered show a gray-green stiff clay that is relatively impervious to moisture, and level areas underlain by diabase are usually poorly drained. The diabase contains much disseminated titaniferous magnetite which can often be found concentrated in small runnels in the fields after a heavy rain.

In this quadrangle, there is an unusual amount of coarse-grained to pegmatitic diabase containing laths of light-gray to pink feldspar and greenish-black hornblende crystals, sometimes approaching an inch in length. It contains a considerable amount of colorless quartz. This rock has not been separately mapped. Its distribution is irregular and patchy, and usually so intimately mixed with the normal diabase that boundaries would be difficult to establish. A sketch map (Figure 63) indicates known occurrences. The pegmatitic rock is thought to be a gravity differentiate, probably near the top of the intrusion.

Diabase of the Morgantown sheet is of the York Haven type of Smith and Rose (1970, and in preparation). A dike sampled near Sinking Spring

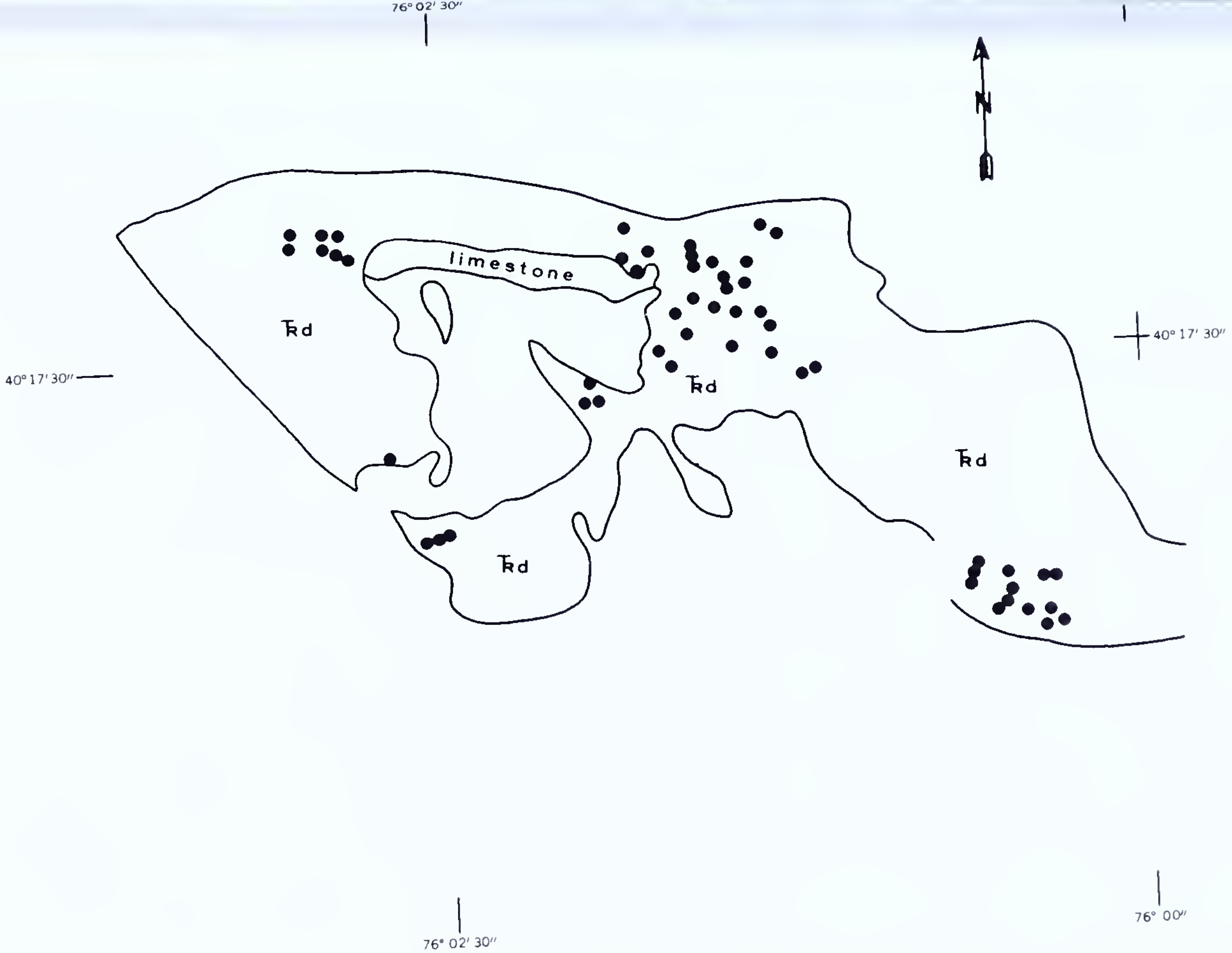

Figure 63. Distribution of known occurrences of very coarse-grained to pegmatitic diabase in the Sinking Spring quadrangle. This phase commonly occurs in the upper part of the intrusion and serves to indicate the facing of the sheet where it may be in doubt.

in the carbonate rock, is of the Rossville type (Smith, personal communication), and it may be suspected that at least some other dikes of the area are also this type. The differences are not apparent in gross mineralogy even in thin section, but they are marked by regionally persistent differences in analyses for some elements. The existence of distinct magmas involved in the emplacement of the sheet and dikes is consistent with a (small) difference in the age of intrusion. Smith and Rose believe that the Rossville type is somewhat older than the York Haven type, not only where originally defined, but regionally. This would imply a sequence of intrusion in this area, opposite to that which is proposed on theoretical grounds and occurs in the Karroo dolerites.

Attitude and form of diabase bodies

Minor Intrusions. Four narrow dikes occur in the Hammer Creek Formation. In no case could the dip be reliably determined, but they are believed to be approximately vertical. This is generally true of such dikes in Pennsylvania, and it is confirmed by two observations on dikes intruding carbonates in the quadrangle. In this area, deviation from the vertical is less than five degrees. A dike extends for several hundred yards east and west near the southern foot of Laurel Ridge near the western edge of the quadrangle. It may be the continuation of a much larger dike in the Womelsdorf quadrangle. This dike appears to be truncated by the fault on the south side of Laurel Ridge, but no offset continuation is known. A well-defined dike was traced for a few hundred yards on the north side of the ravine south of Buzzard Road. A small dike lies east of U. S. Route 222 about 1,000 feet south of Blimline Hill Road. Several small diabase pods of greater thickness extend this trend northward for about 0.6 miles. These bodies are aligned parallel to and about 500 to 1,000 feet from the Little Muddy Creek fault. It seems plausible that these bodies have risen along fractures associated with the major fault, implying the existence of this fault before diabase emplacement, though the last fault movement was clearly subsequent, at least to emplacement, of the Morgantown sheet. On a hill about a mile northwest of Vinemont, two small pods of diabase, comparable to the preceding ones, appear approximately in alignment with a very narrow fine-grained dike. In this case, the alignment does not occur in a fracture zone recognized by other criteria; but they do occur in a transverse saddle in the resistant conglomerate ridge, and some shattering, if not appreciable displacement, may be suspected. None of these small patches show any evidence of much larger igneous bodies beneath them, for metamorphism of the sediments is seen only very close to the contacts, and no magnetic indications whatever have been recorded.

Morgantown Sheet. The Morgantown sheet is only one of a number of such sheets prevalent through the whole length of the Triassic belt in Pennsylvania. These sheets are roughly saucer shaped and exhibit both concordant and discordant relationships with the enclosing strata. These sheets have been studied regionally by Hotz (1952), who concludes that they are comparable in scale, style, and origins to the Karroo dolerite (diabase) sheets of South Africa. The exact mechanics of the emplacement of such sheets is somewhat in doubt; but they appear to be all emplaced at about the same level, presumably reflecting the bouyancy effect of the density differential between the magma and the overlying sediment. There are numerous local irregularities in these sheets which may reflect anisotropy in the rock fabric or conditions of the local stress field at the time of intrusion, but knowledge of the general form of the sheets places some limitations on the geometry that may be reasonably inferred where the local evidence is inconclusive.

An aeromagnetic study of southeastern Pennsylvania by the U. S. Geological Survey has resulted in the publication of a number of quadrangle magnetic maps, including the Sinking Spring quadrangle (Bromery and others, 1961) and a regional aeromagnetic map (Bromery and Griscomb, 1967). The latter clearly shows the exposed margins of the Morgantown diabase sheet marked by a distinct belt of strong anomalies surrounding an area of relatively high magnetic intensity but less local magnetic relief reflecting the subsurface connection of the diabase exposure and confirming the saucer shape.

Where the main diabase enters the quadrangle east of Colonial Hills it starts to change trend, and probably dip, almost precisely at the eastern margin of the map. In the western half of the Reading quadrangle, the strike is about due east and the dip is evidently quite steep as shown both by the reduced width of the crop line with respect to the west where a moderate dip is inferred, and by the symmetrical placement of magnetic contours. At the quadrangle boundary, the crop swings northwestward and about doubles in width. In a general sense, this trend persists to where the crop splits around the Wheatfield area.

Along U. S. Route 222 at Colonial Hills, the trace of the boundary on the hill slope west of the highway indicates that the diabase probably dips southwestward under the sediments. The extent of metamorphism in the sandstone southwest of the diabase also suggests the presence of the intrusion at no great depth, which again favors a southwestward dip of the sheet. Bascom and Stose (1938) indicate the contact metamorphic zone developed in Triassic sediments adjacent to the Morgantown sheet in the Morgantown area is about 500 feet thick. Assuming this figure is valid in the Sinking Spring quadrangle, the dip of the diabase along U. S. Route

222 may be approximated as not greater than 24½° by the distance from the contact to the southernmost solid crop of metasediment at the junction with Goose Lane, nor less than 14° from the distance to the first outcrop of unbaked sediment to the south. The attitude of metasediments in the Colonial Hills area is discordant with respect to all other beds in the southeastern part of the quadrangle, but they strike parallel to the diabase contact and dip the same as the bedding, that is about 14 to 15°. Attitudes of beds along U. S. Route 222 north of the sheet also approximate its general trend but have an average dip of about 35°. If this contact is also conformable, the dip thus established seems quite consistent with the magnetic data and the complex form of the sheet that must exist to the west.

Continuing westward along the diabase to the Wheatfield Mines area, the diabase splits apart and encloses an inlier of Newark sediments and some Lower Paleozoic rocks. The ridge of diabase at the north border, north of Wheatfield Road, probably dips much more steeply to the south, probably about 45 degrees from reports of old mine workings (d'Invilliers, 1883), though the general prevalence of metamorphism throughout the inlier makes it seem improbable that this dip extends to any great depth. The magnetic pattern (Bromery and others, 1961) tends to support this southern dip but the magnetic pattern is complicated by small local anomalies which are produced by some remaining magnetite ore at depth in the Wheatfield Mines.

At its western end near Fritztown, the diabase exposure hooks sharply southeastward. Bran Road lies almost along the contact with the sediments to the west. This western edge of the diabase is marked by a sudden drop toward a magnetic low, and it is inferred that the attitude of the contact is very steep. Other evidence indicates that this contact is the trace of a major fault (see "Structure", below).

The very ragged form of the diabase boundaries in the area east of the "hook" and south of Wheatfield Road suggests that the diabase here dips gently under the sediments of the Wheatfield area. At only one place in the area was there any suspicion of faulting. Further, nearly everywhere the diabase immediately adjacent to the sediments shows an extremely fine grain nature that is characteristic of the chilled contact zone. There is little or no indication of a great disturbance of the sediments near the diabase border. This is essentially the relationship which was deduced by Spencer (1908).

An alternative hypothesis, which is plausible on the map pattern, is that the general low southerly dip found in the main limb near Colonial Hills flattens further into this limb and the sediments of the Wheatfield area are exposed by erosional breaching. The latter proposition seems inconsistent with the general magnetic intensity over the Wheatfield area and known occurrences of the pegmatitic facies of the diabase (Figure 63) which suggest that it is the upper contact of the diabase adjacent to the Wheatfield area sediments.

The irregular area of diabase immediately north of the junction of Goose Lane and Chapel Hill Road is marked by the most conspicuous magnetic high in the Morgantown sheet outside known areas of magnetite concentration. It is superimposed on the broader high that covers the region inside the "hook".

The absence of a conjugate magnetic low with this anomaly, as is prominent at known magnetite concentrations such as Cornwall and especially Morgantown, suggests that this anomaly does not arise from such a concentration but reflects a local thickening at the diabase sheet. Socolow (1961) indicates no evidence of economic mineral concentrations, and oral reports claim the anomaly area was test drilled with negative results for economic iron concentration.

The southern margin of the diabase lying south of the Wheatfield area is also quite irregular and likewise suggests a low dip to the south as is a logically necessary consequence of its connection to the simple margin of the Morgantown sheet to the east. In this case, there are no known occurrences of the pegmatitic diabase to confirm the identification of this contact as also being an upper contact of the sheet, but the aeromagnetic pattern leaves little doubt that this is the correct interpretation. As there is no indication of any excess thickness of this part of the sheet except in the Goose Lane area, it would appear that the diabase south of the Wheatfield area represents an upwarped axis in the sheet. Considering the high structural competence of the diabase sheet, it seems that this axis must represent some influence effective at the time of intrusion. It is tentatively suggested that this, in fact, represents the locus of encroachment of the diabase into the Paleozoic rocks.

The extension of the Morgantown sheet west of the Little Muddy Creek fault is shown by its irregular margins and wide metamorphic belt to be an essentially tabular discordant element dipping gently east northeastward to easterly. In the deep embayment eroded by a ravine in the southwestern corner, a dip of about 9° is calculated from the outcrop pattern and this value appears to be representative of the mass. Outcrops of medium- to coarse-grained diabase occur at several places along the former electric railway on the west bank of Little Muddy Creek. The presence of contact-chilled fine-grained diabase along the northern, western, and southern edges shows that all these contacts are intrusive and not appreciably affected by faulting. The eastern edge is obscured by recent alluvium along the course of Little Muddy Creek, but this is also the course of a major fault. The magnetic pattern over this element is entirely consistent with the deduced shape and eastward dip. The intensity of the anomaly is less than that associated with the margins of the main body to the east which accords perfectly with the observation that only the lower contact and a partial thickness is preserved.

Thickness of intrusions

Dikes. Reliable thickness determinations of diabase dikes in the Hammer Creek Formation were not recorded in the Sinking Spring quadrangle. On the basis of the float line, they are noted as narrow or very narrow. Regionally, dikes of this type rarely persist with a thickness appreciably in excess of 100 feet, and about 50 feet is typical for prominent dikes which have been traced many miles. On this basis, the thickness of the Sinking Spring dikes should be understood to range from not more than a few feet to less than 50 feet.

This range is entirely consistent with a few observations on presumably syngenetic dikes in carbonate rocks of the quadrangle. The dike extending east northeast from the foot of South Mountain, north of Fritztown, is about 30 feet thick at its western end. For about 1.5 miles eastward, it forms the spine of a low ridge and presumably maintains about the same thickness. From this point, it thins and possibly becomes discontinuous south of Sinking Spring Borough. Near its eastern known limit it is about 2 feet thick at Pa. Route 724. The dike entering the quadrangle near the northeast corner extends more than two miles east northeastward to the Schuylkill River. It is 15 feet thick where it crosses Tulpehocken Creek, three quarters of a mile from the quadrangle boundary. It evidently thins southwestward as it cannot be traced between Pendergast Road and State Hill Road. Continuing the same trend and probably continuous at depth, a dike extends nearly 1.5 miles southwestward from the vicinity of State Hill Road. This dike is evidently continuous in float though exposed only in the area mentioned below. The thickness is estimated to be nowhere greater than 20 feet with one exception, and it is probably not in excess of 5′ in the western segment.

In the segment of the latter dike which follows the trace of a known fault, there is an elliptical mass of diabase about 100 feet wide. This mass occurs where the high-angle fault cuts a low-angle thrust. Considerable shattering of the county rock is indicated in this situation, and it is supposed that this is the essential factor localizing the pod. A similar origin is consistent for the elliptical diabases in the Little Muddy Creek Valley. The other occurrences of such bodies do not have known structural controls, but the analogy is plausible.

Morgantown sheet. Exposure in the Sinking Spring quadrangle is not favorable for a precise determination of the thickness of the Morgantown sheet in this area, but several approximations yield values consistent with sheet thickness determined elsewhere.

The body west of the Little Muddy Creek fault has about 320 feet of diabase preserved at its eastern edge and thins westward if the calculated local dip of 9° is generally valid. The upper contact and some part of this mass have definitely been removed by erosion. On the basis of relative magnetic intensity it is estimated that the remaining thickness is probably less than half that of the sheet to the east.

Definite upper and lower contacts of the sheet occur only in the Colonial Hills segment. Irregularities in the trace of the contacts probably reflect some variation in both the mean attitude and thickness of the body; and the dip is only approximately known, but certain limits may be established. The least possible dip of the upper contact along U. S. Route 222 has been established as 14°, which is consistent with the assumption that it is locally concordant. The lower contact here is probably steeper — perhaps about 35° parallel to bedding in this area. It would be consistent with regional patterns, however, if this rapidly decreased with depth to approximate parallism with the upper contact, and the assumption of a parallel-sided body dipping 14° is not too unrealistic for a minimum thickness calculation. On this basis, the indicated minimum thickness near the road is just under 900 feet. If we suppose the minimum dip persists to the narrowest part of this segment, about 500 yards northwest, ultimate minimum thickness indicated is 715 feet. The maximum possible dip of the upper contact along the road was estimated at 24½°, which, coincidently or not, is exactly the mean of the dips of the adjacent sediments near the upper and lower contacts. Again, assuming an essentially parallel-sided body, this value approximates the maximum probable mean dip of the body, and the indicated maximum thickness along the road is 1,490 feet. If this dip persists northwestward to the narrow zone the indicated thickness is 1,120 feet, which is in good agreement with typical values recorded for Pennsylvania diabase sheets elsewhere, such as 1,200 feet at Cornwall. The most extreme assumption which seems plausible in the structural framework is that the 45° dip in the Wheatfield area persists southeastward to the narrow zone. The indicated thickness of 1,780 feet is almost certainly excessive, but it provides an extreme upper limit for speculations. The median of the limiting values is about 1,250 feet, which again approximates typical regional values. Twelve hundred feet has accordingly been adopted as the usual thickness of the Morgantown sheet in this area for the purpose of constructing cross sections.

The segment of the sheet north of the Wheatfield area dips about 45° south at the Wheatfield Mine, according to old reports. The indicated thickness here is 712 feet, though the northern contact may be faulted. Considering the irregular form of the sheet in this area and the fact that it is cutting into rocks with quite different properties than elsewhere encountered adjacent to the sheet, this value, which approximates the minimum possible value calculated to the east, may not be unreasonable for the total thickness of this segment. The question of faulting at this locus is considered in the section on the North Border fault.

Metamorphic effects

Adjacent to the diabase sheet, the Triassic sediments have been appreciably metamorphosed. Red shale close to the contact has its hematite completely reduced to magnetite, and the rock is dark gray, black, or purplish-black hornfels, extremely tough, and breaks with a conchoidal fracture. Locally, it contains knots of epidote or cordierite. At greater distances from the intrusive, the shale is medium to dark gray and less indurated. Siltstones become altered to light or medium gray siliceous hornfels. The quartzose sandstone and conglomerates become light gray, brittle quartzite in which garnets are recorded at occasional stations. In some areas, notably in the Lebanon (Gray and other, 1958) and Richland (Geyer and others, 1958) quadrangles, the siliceous metasediments often become more resistant to erosion than the diabase. This condition is not conspicuous in the Sinking Spring quadrangle, but it may in part account for topography associated with the Morgantown sheet west of the Little Muddy Creek fault. Here the diabase lies in the hill slope and the metasediments stand above it.

The zone of metamorphism, as shown on the Geologic Map (Plate 1), is very generalized. According to Bascom and Stose (1938) the metamorphism affects about 500 feet of Triassic sediments adjacent to the southern part of the Morgantown sheet. This figure has not been confirmed in the Sinking Spring area, but it seems reasonable.

Thermal metamorphic effects on the Paleozoic carbonates where they come in contact with one of the major diabase sheets is also quite profound, though the effects of the minor dikes are almost imperceptible. Where the diabase sheet comes in contact, the carbonates are strongly recrystallized, tending to lighten their color and obliterate any remnants of original sedimentary fine structure. It is these effects, combined with poor exposure in the Wheatfield area, which make determination of the stratigraphic position of the carbonates in this area quite uncertain. In addition, the carbonates, whether Paleozoic or Triassic limestone conglomerates, are sporadically a locus of considerable metasomatism and iron mineralization, a feature which has produced the great magnetite deposits at Cornwall and Morgantown, as well as the rather minor deposits at the Wheatfield Mine and a number of other areas.

At Cornwall, there is a considerable body of shaly rock, the Mill Hill slate, evidently equivalent to the Martinsburg or Cocalico Formations, which owes its present character largely to the effects of metamorphism by the diabase. The phyllitic rock at the western end of the Wheatfield Paleozoic belt, called Martinsburg Formation in this report, was in several places in McLaughlin's notebooks, identified as Mill Hill slate, or "like Mill Hill". This rock is distinctly different from typical metamorphosed Triassic shale of the Hammer Creek Formation. These differences may arise in part from initial differences in composition, but are probably, for the most part, a consequence of the fact that the Paleozoic shales were, in fact, already substantially metamorphosed phyllites with strong foliation prior to the thermal event.

The Hardyston Formation is predominantly quartz and somewhat metamorphosed on a regional basis. It is not, therefore, remarkable that little thermal effect of the Triassic intrusions is seen where they lie adjacent to the Hardyston. In a quarry on Gelsinger Road, about 1,000 feet east of Chapel Hill Road, the Hardyston near the Triassic contact is dark and vitreous and seems considerably more indurated than typical elsewhere. This may well be an effect of the intrusion. If this is correct, it would suggest that there was little faulting south of the Hardyston, at least after the intrusive phase.

STRUCTURE

General Statement

The structure of the Newark rocks in this quadrangle is broadly a north northwestward-dipping homocline, broadly warped about a northwest plunging axis and block-faulted in the western part, modified by local folds plunging northeastward near Camp Indiandale and reversed dips adjacent to the north border of the basin. The northern border itself is a major fault over the western half of the quadrangle, and possibly over its entire width.

Dips of the sandstones and conglomerates in most of the area are northwestward or northward, ranging commonly from 15° to 30°, and sometimes exceeding 40°, with a modal value of 23° in a north 27° west direction for all readings. At the southern edge, near Adamstown, northeasterly dips are found. Numerous southerly and easterly dips near Camp Indiandale express local sharp folding. Southwesterly dips occur on both sides of the large diabase body that crosses U. S. Route 222 near Colonial

Hills. Southerly dips along the north foot of Laurel Ridge are interpreted as the result of drag along the north border fault. Locally, in the broad area of sandstone north of Vera Cruz, the strata are probably nearly horizontal or undulate gently.

All recorded bedding attitudes are summarized stereographically in Figure 64. The diagram reflects all the observed trends but does not isolate them geographically. The significant feature is the strong, almost polar, maximum which shows the tilting as the dominant deformational event. The westward component of tilting evident here is discordant both to the local trend of the basin and the regional trend of the basin segment between the Susquehanna and Schuylkill Rivers. It is also discordant to the deflection to be anticipated from the reduction of width of the basin and increase of dip which occurs at about this longitude (Figure 66). Only the scattering of northeasterly dips observed near Adamstown seem to reflect this last trend. The westward component is not a local anomaly, but part of a broad scale northwest plunging fold system which is shown to be regionally prevalent in Figure 65. The local influence of this system is seen in the elongation of the high level contours and the minor isolated submaximum in Figure 64.

Folding

The northward regional tilt of the Triassic sediments is a species of folding in which faulting undoubtedly plays a part in the Sinking Spring area, but for which faulting is not an adequate explanation. Numerical calculations from data in the western half of the Sinking Spring quadrangle and the Womelsdorf quadrangle suggest an order of magnitude discrepancy between known fault displacements and those required to produce such dips by faulting. Such calculations become mere academic exercise when it is noted that there is little change of dip to the west in the Richland and Lebanon quadrangles, where the strata overlap the older rocks unconformably. Regardless of what faulting may be hypothesized south of the overlap, it is irrelevant to the northward dip of the overlapping strata, except insofar as it might tend to reduce it by drag effects. There is no reason to doubt that the process effecting the tilting of strata in the areas of overlap was competent to produce comparable results throughout the basin.

The nature of this process is problematical, but tilting the strata into the unconformity apparently requires a horizontal component of compression. This observation is consistent with the surprising number of occurrences of subhorizontal slickensides in the Triassic rocks of the Sinking Spring area. In the absence of a defined hinge or arch, the term folding is hardly rigorous, but the process seems to be mechanically related.

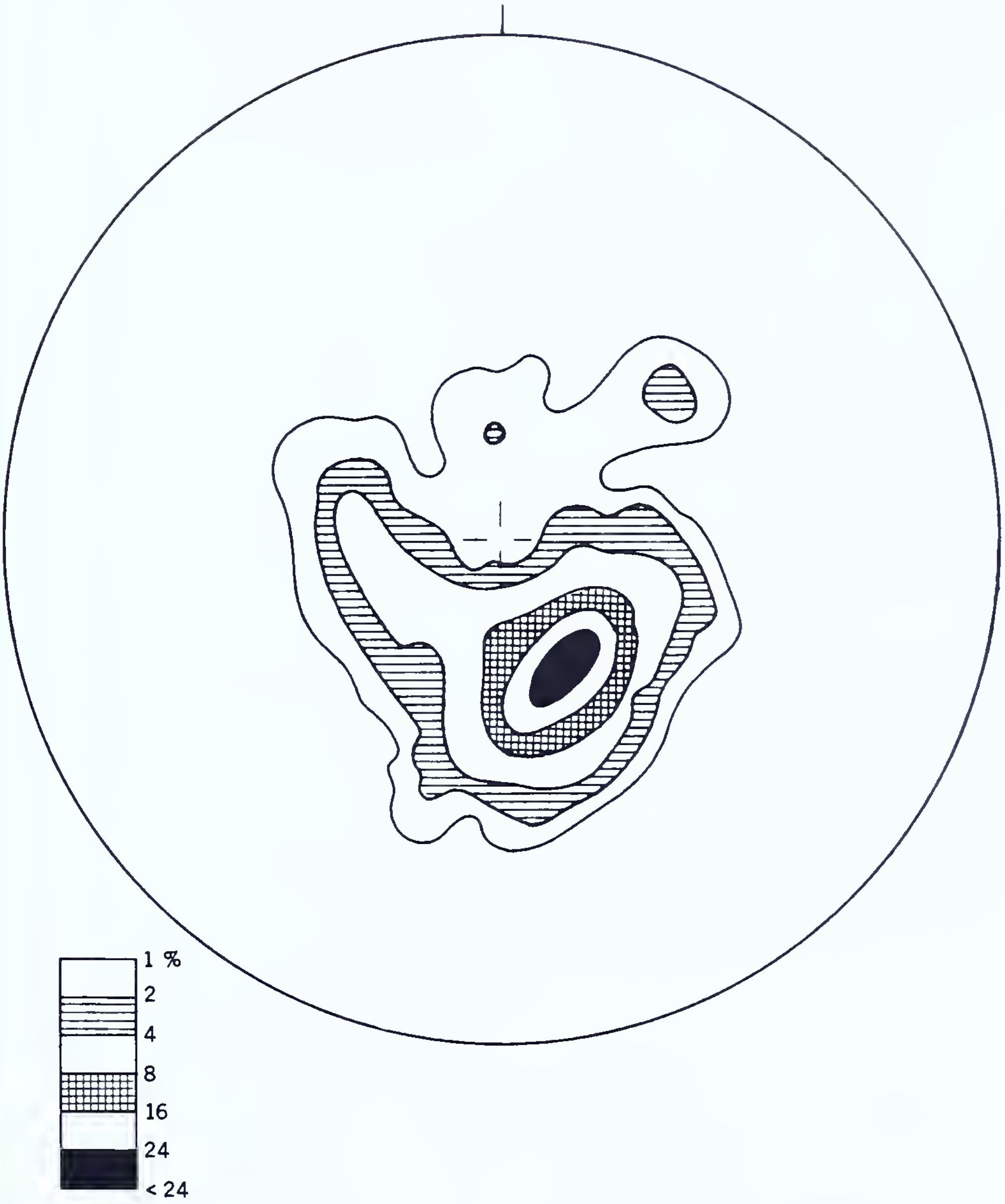

Figure 64. Contours of 275 poles to bedding in Triassic sediments of Sinking Spring quadrangle. All measurements believed reliable have been included.

The trace of conglomerate beds in the vicinity of Vinemont suggests several gently warped northwest plunging folds of nearly two-mile wave length. In area A of Figure 67 these folds appear to be expressed without interference by effects of the border faulting or folds of different trend to the south. Bedding attitudes in this area are plotted on Figure 68a and

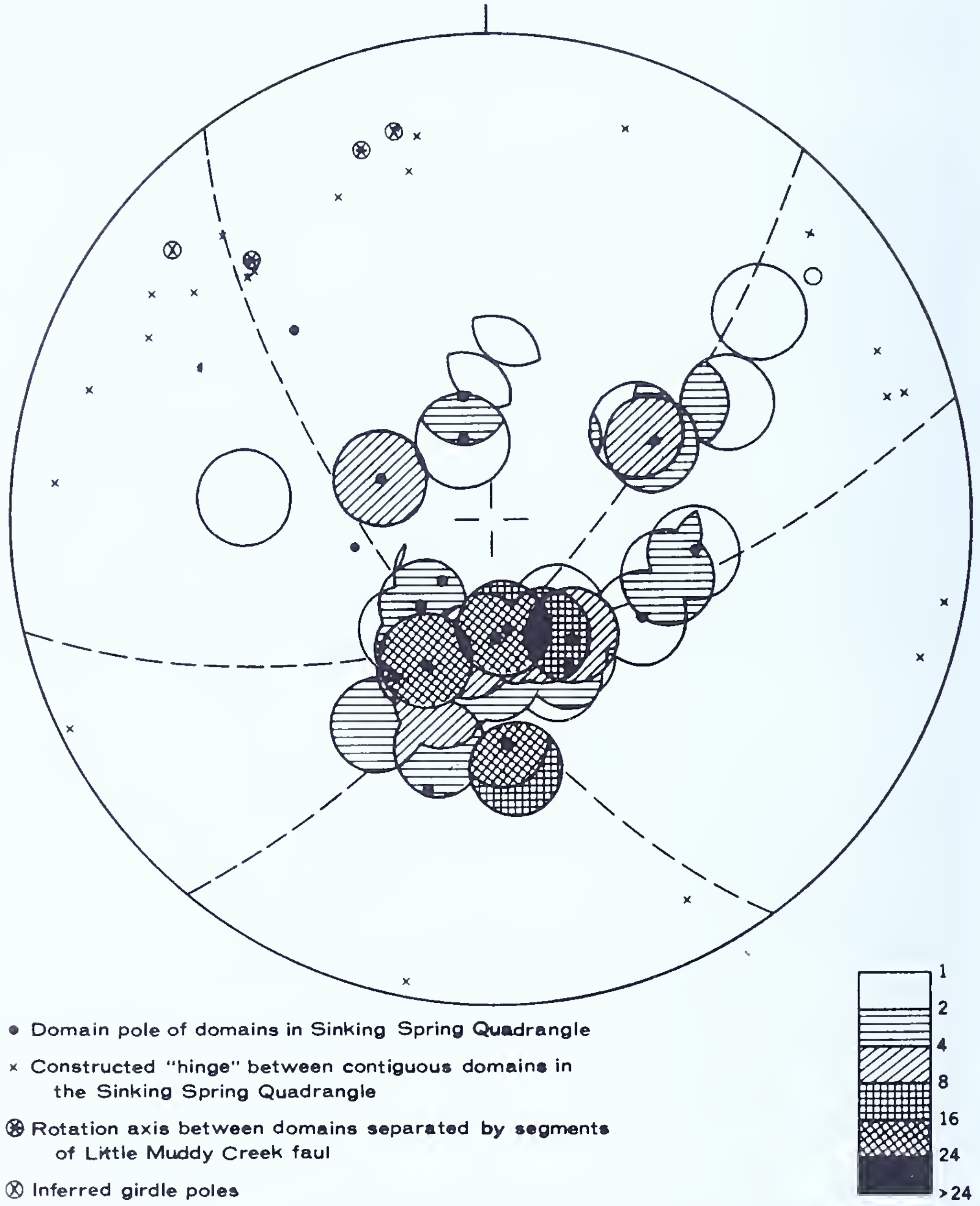
● Domain pole of domains in Sinking Spring Quadrangle
× Constructed "hinge" between contiguous domains in the Sinking Spring Quadrangle
⊛ Rotation axis between domains separated by segments of Little Muddy Creek faul
⊗ Inferred girdle poles
1
2
4
8
16
24
>24

Figure 65. Stereograms of regional dips of Triassic sediments between longitude 75°45′W and 76°15′W. Data comprise 40 domains statistically homogeneous with respect to bedding attitude as determined from 537 stations by Faill (1969). Contours by Mellis method weighted for number of observations per domain. The use of domains introduces certain irregularities in the distribution, but the resemblance to Figure 64 is obvious. Minor features of the diagram are discussed in the text. The girdle with northeastward

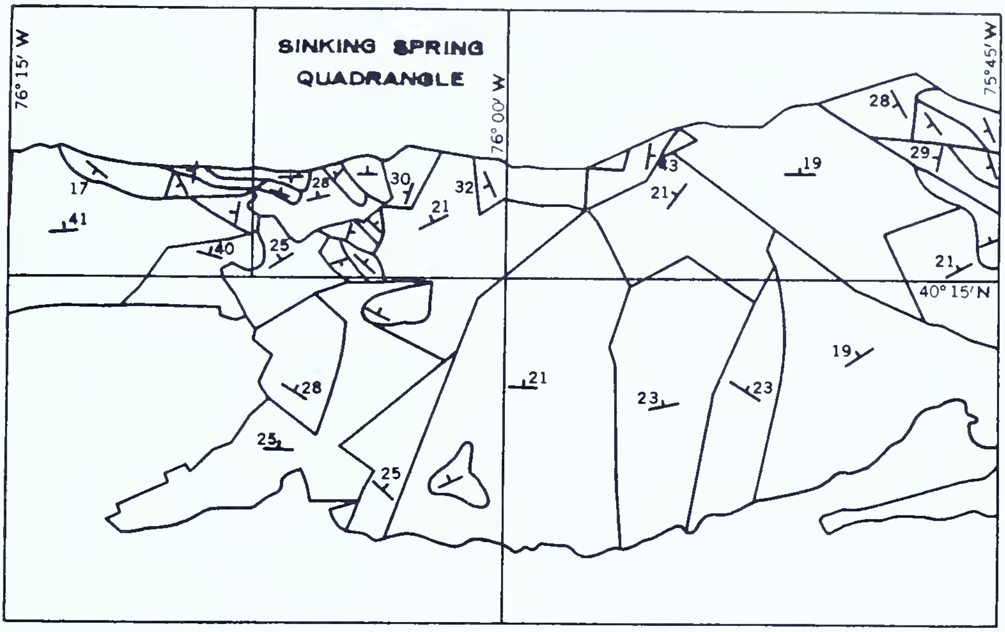

Figure 66. Domains of statistically uniform bedding of Triassic sediments in Wernersville and Reading 15-minute quadrangles as defined by Faill (1969). Domains vary considerably in size and data density, but the larger domains which dominate the gross structure are quite distinct. The smaller domains in the Sinking Spring vicinity are actually less homogeneous and reflect the change in mean dip from the narrow and more steeply dipping part of the basin to the west to the wider eastern portion.

confirm this trend. The trend, as previously noted, is evidence of the elongation of the higher level contours in Figure 64, and it is consistent with the more northerly of two northwest plunging trends inferred regionally in Figure 65.

Beds in area B of Figure 67, in general, have attitudes comparable to those in area A. However, there are some southerly dips in the area which are presumably related to movements on the border fault. To preserve definition of the trend in area A, area B was erected to include all such observations. In the west, the fault south of Laurel Ridge provided an objective boundary; eastward the boundary is simply carried about 2,000 feet south of the border fault. Stereographically, the majority of beds

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plunging axis which is not an obvious best fit for this diagram is taken from Figure 68c because the latter is believed to represent the only significant component of this trend.

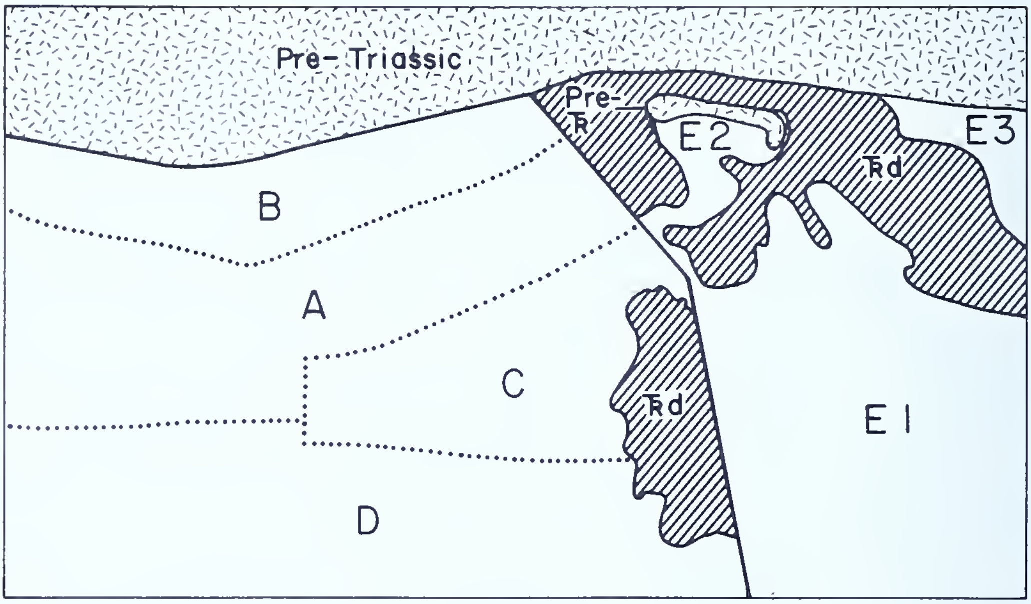


Figure 67. Southern half of Sinking Spring quadrangle showing areas covered by bedding stereograms of Figure 68.

Figure 68. Stereograms of bedding Triassic rocks.

a) Seventy-five poles to bedding in area A of Figure 67 with girdle and girdle axis in Jacksonwald trend.

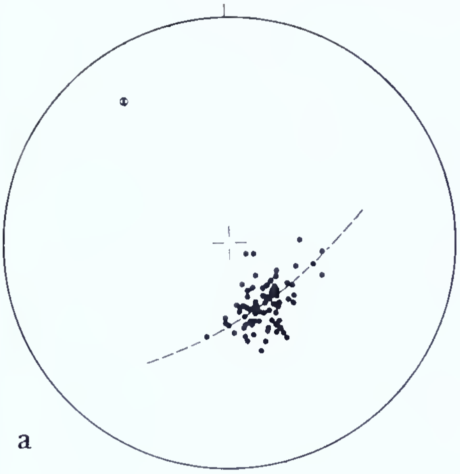
b) Thirty-eight poles to bedding in area B of Figure 67. Major fabric is similar to A but scattered readings reflect effects of faulting at the Triassic border.

c) Sixty poles to bedding in area C of Figure 67 with girdle and girdle axis in unique local trend.

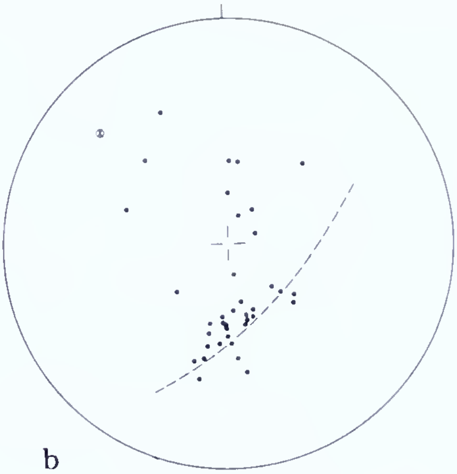
d) Thirty-one poles to bedding in area D of Figure 67. Data are deemed insufficient to define any clear trend.

e) Fifty-one poles to bedding in area E_1 of Figure 67 (points), nineteen poles to bedding in area E_2 (circles), six poles to bedding in area E_3 (enclosed group of points). For discussion of girdles see text.

f) Poles to bedding in area E_3 and immediately adjacent portions of Reading quadrangle showing unique fold trend.



a



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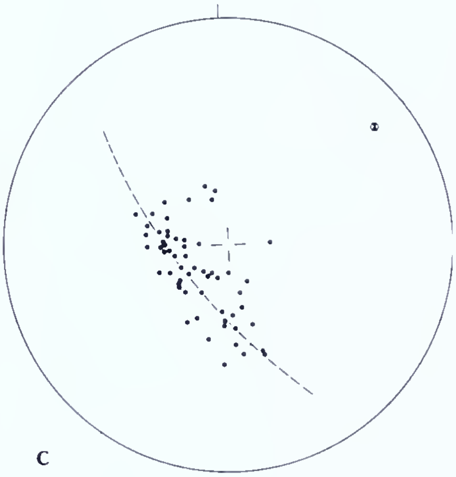

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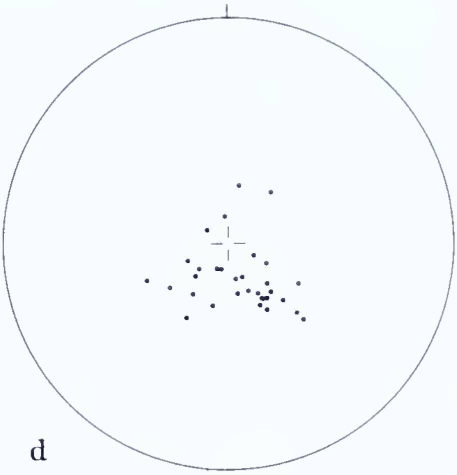

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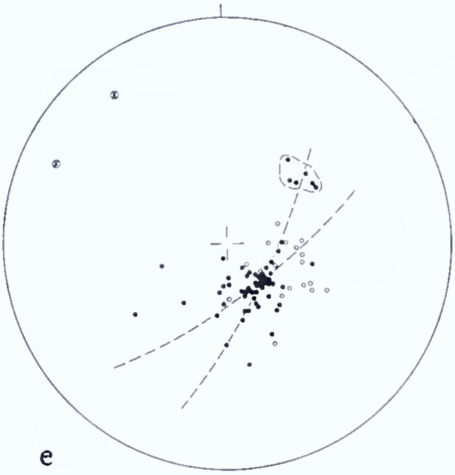
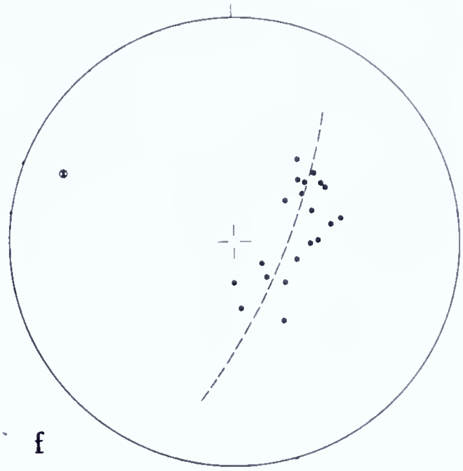


e



f

show about the same distribution as in area A (Figure 68b), as anticipated. The considerable geometric scatter of the elements with southerly dip shows no preferred orientation of rotation with respect to the dominant bedding trend in the area. This pattern is entirely consistent with a complex of local fault drag folds but not with any systematic folding.

About two miles south of Fritztown, the normal northward dips are interrupted by a prominent syncline and a complementary anticline north of it. The synclinal axial trace trends nearly east-west along a spur rising to the crest of the highest hill of the area (elevation 1,060 feet) southeast of Camp Indiandale and then somewhat to the north of east across more level ground. Dips on the south limb average about 25°. On the north limb, they are slightly less near the nose of the fold and apparently become gentler as the strata are followed northeastward along the strike. This decrease of dip is indicated by a few dips on scarce outcrops and particularly by the apparent fanning out of alternating and poorly-defined conglomerate and sandstone submembers (see the sketch map, Figure 62). The conglomerates appear to finger out eastward here and grade into sandstones. Eastward, toward Mohns Hill, there are no outcrops on which dips can be measured, but the trends of traceable bands of conglomerate indicate that dips become quite gentle there. At a glance, the map pattern seems to suggest that the diabase is discordant to this fold and implies that the folding preceded the intrusion. With the eastward decrease of dip, however, the geometry of the diabase contact deviates little from the projected fold profile, and the diabase appears to have been warped simultaneously with the folding of the sediments. The high competence of the diabase relative to the sediments and a presumably decreasing competence gradient across the metamorphic zone seems to provide an excellent explanation for the changing geometry of the fold. Regionally, the weight of the evidence is that intrusion preceded deformation of the sediments. The possibility that local folds of anomalous trend may be older than the diabase should be considered, but contrary indications allow simpler explanations.

The complementary anticline north of the syncline is indicated by a dome-like structure west of Indiandale Road and by the abruptly curved and cuspate outcrop of conglomerate members east of Vinemont Road. The anticlinal axial trace trends northeastward. No exposures on which dips could be measured were found toward the eastern end near Mail Route. Between the two areas just mentioned, the anticline contains a "saddle" formed by a transverse northward-striking syncline south of the lake at Camp Indiandale.. The common limb of anticline and syncline is traversed by a branching fault that is described in the section on "intrabasinal faulting".

Despite some divergance of their axial traces, stereograms of both folds show essentially identical plunge of the fold axes. Together, the two folds form a domain homogeneous with respect to orientation of rotation. This domain is shown as area C of Figure 67 and the bedding attitudes are collected in Figure 68c. By inspection of other diagrams on this figure, it is obvious that this trend is unique to area C in the Sinking Spring quadrangle. Furthermore, if the distribution of domain poles occurring in the Sinking Spring area, shown as points on Figure 65 is considered, it is evident that the northeast plunging trend suggested by the regional pattern is dominated by domains in this area. Thus, the trend in area C is regionally, as well as locally, unique.

The divergence of the axial trace of the syncline from its plunge azimuth is most pronounced in the area of highest data density immediately south of Camp Indiandale. It cannot, therefore, represent an artifact of defective data distribution or a variation in strike of the axial surface. The only possible explanation is that the axial surface dips northward at a surprisingly low angle, and the deflection of the trace is a topographic effect. Crude construction from measurements on the map indicate that the dip of the axial surface cannot be much greater than 20°. The axial trace of the anticline is much more consistent with its plunge, and the axial surface is evidently near vertical. There appears to be no obvious explanation of this geometry, but the folds are a local phenomenon restricted to one side of a major fault. They evidently represent the product of a stress field anomaly produced by fault movement which is not readily amenable to theoretical analysis.

South of the distinctly defined folds of the Camp Indiandale area, the density of stations yielding reliable bedding attitudes is not great. Dips are predominantly northerly, more or less in the regional trend, but there is considerable variation in strike and some dip reversals occur. For completeness in the analysis, attitudes from this area (area D of Figure 67) are collected in Figure 68d. The data are not considered sufficient to define any significant trends. The few northeasterly dips in the southeast corner near Adamstown are part of a larger domain of relatively uniform bedding extending south of the quadrangle. Bedding in this orientation does not really fit the pervasive northwest fold trend nor the local trend of area C, but it does have about the attitude to be anticipated from a connection between the belt of dips generally greater than 40° in the narrow western part of the basin and the somewhat gentler dips prevalent through most of the Sinking Spring quadrangle and throughout the wider, eastern part.

East of the Little Muddy Creek fault, bedding is quite uniform south of the diabase sheet (area E1 of Figure 67), except in the vicinity of Colonial

Hills. At Colonial Hills, bedding traces and a few dip readings suggest a possible northwest plunging fold. This is an area of poor exposure and metamorphism which may be separated from the homocline to the south by a fault. Bedding attitudes from area E1 are shown on Figure 68e by the solid prints exclusive of the enclosed cluster which represents attitudes from area E3 (Figure 67). In the E1 group there is a suggestion of possible elongation of the highest density of poles along the girdle of the northwest fold trend, but the concentration is essentially polar.

Bedding attitude is somewhat more variable in the Wheatfield area (E2 of Figure 67) as is shown by the open points of Figure 68e. Taken together, however, the overlapping E1 and E2 distributions form a pattern quite similar to area A and show the same northwesterly fold trend. The relation between these areas is consistent with the regional pattern and not evidently much influenced by the diabase intrusion. This is a point of some significance, for if the arch in the diabase sheet separating these areas was a product of post-intrusive deformation, clearly perceptible rotation between the domains around a northeast trending axis should be evident.

The isolated cluster of bedding poles in Figure 68e are from area E3 (Figure 67) which lies on the opposite side of the diabase sheet. The proposition that this domain is part of a real fold relative to E1 is entirely consistent with the fold trend conspicuous in the regional data (Figure 65). The domains of strong southwesterly dip which give this trend its clear definition are predominantly associated with the Jacksonwald syncline, a clear flexural fold. The same relationship in this area, however, is not proved by the data of Figure 68e. By extending observations from area E3 eastward into apparently continuous beds in the immediately adjacent part of the Reading quadrangle, the attitudes in area E3 are seen to belong on the limb of a distinct fold (Figure 68f). This fold does, in fact, have an axis congruent with the inferred rotation between E1 and E3, and it fits the few readings from the Colonial Hills area which did not fit the general homocline of E1.

The area east of the Little Muddy Creek fault has two distinct northwest plunging fold trends, E1-E2 and E1-E3 a feature which is also evident in the regional data. There seems to be three possible explanations for this relationship. There may be a single, regionally pervasive but rather variable, fold system in which apparent discrete differences in plunge azimuth may be an artifact of the sampling distribution. There may be two distinct trends, each characteristic of its own subregion; or two distinct trends may, to some degree, co-exist and interpenetrate. To examine these alternatives, the implied hinges or rotation axes separating contiguous domains of Figure 66, which lie in or enter the Sinking Spring quadrangle, were constructed (Figure 65). In view of the statistical nature of these domains and the method of their construction, some random scatter in the orientation of their mutual boundaries is expected, but concentrations showing preferred orientations are significant. It is evident that such concentrations exist in the northeast and northwest quadrants of the diagram; whether or not the latter is truly bimodal is arguable. It is impracticable to geographically distinguish the domain boundaries in the diagram, though it does bear on its interpretation. As should be anticipated, domains generating the axes forming the northeastern concentration are associated with area C, the local folds near Camp Indiandale. Interdomain axes contributing to both the more northerly and more westerly components in the northwest quadrant are geographically scattered across the quadrangle. This distribution is consistent with either a single variable fold trend or two interpenetrating northwesterly fold trends but not with (complete) subregional differentiation between two fold trends.

For discrimination between the two hypotheses, amenable with the geographic distribution of interdomain axes, two points seem particularly significant. These have been distinguished by a special symbol on Figure 67. They represent the rotation between domains adjacent across both the more northerly and more westerly trending segments of the Little Muddy Creek fault. In each case, the implied rotation axis is essentially parallel with the trend of the fault segment, and the sense of rotation is consistent with known fault displacement. Furthermore, each of these fault-related rotations coincides with one or the other of two discrete northwesterly-plunging fold directions implied if the clustering of interdomain axes is taken to be bimodal. This fact has two important implications: that the folding is directly related to the faulting and that the bimodal distribution is real.

In evaluating the relationship between folding and faulting, the character of the folds should be considered. While some local variation in bedding strike may be related to warping about a northwesterly plunging axis at a relatively small scale, clearly definable folds of this trend have a wave length of a mile or more. That is probably less than, but in the same order of magnitude as, the (preserved) thickness of the Triassic basin fill. It is unlikely that folding of this scale is independent of the pre-Triassic basement. It is also unlikely that widespread compressional folding of the pre-Triassic rocks within the basin oblique to the basin trend would fail to leave an impression in the older rocks beyond the basin limits. Data from the Paleozoic rocks are therefore relevant. Stereographic methods, unfortunately, will not serve to detect such impression because the trend sought has the same general orientation as the Paleozoic crossfold B_2'. The B_2' folding, however, is generally a small-scale feature, while the broad transverse folds affecting Triassic rocks should be evident in the map trace of essentially planar elements, such as the Paleozoic thrusts, as mild sinuosity comparable to that shown by the conglomerate beds of area A. No such sinuosity is apparent on the geologic map, hence it is concluded that northwest trending folds of the pre-Triassic rocks, analogous to folds found in the Triassic sediments, do not exist.

An explanation of the Triassic folds which is consistent with all present information is that they developed in superficial sediments as the result of differential movement of blocks in a fracture mosaic in the pre-Triassic rocks, activated by depression of the basin. Only where movement on the basement fractures was large, as at the Little Muddy Creek fault, need the fractures propagate to the surface. Elsewhere their influence may be expressed as hinges between tilted domains; that is, fold axes. The presence of several spatially co-existent preferred orientations in a fracture mosaic is expectable; and the presence of geographically interdispersed interdomain hinges with bimodal orientation is explicable on this basis. In the same light, the scattering of diversely oriented interdomain hinges of Figure 65, considered random in the first approximation, may represent the activation of fractures in the mosaic other than those on the dominant trends.

If the domains of Figures 65 and 66 owe their identity to a basement fracture mosaic, the preferred orientation of activated fractures as reflected by the stereographic concentrations of interdomain hinges may have mechanical significance in relation to the regional tilting. It was previously asserted that certain features of regional tilting seemed reconcilable only with a compressional deformation. Regional compression, in this case normal to the basin axis, often is accompanied by some measure of extension perpendicular to the compression. In this situation, preexisting fractures perpendicular or steeply inclined to the compression would have higher than lithostatic-normal stress while those parallel or subparallel to the compression would have less than lithostatic-normal stress. This stress difference will obviously have an effect on the ease with which fractures in various orientations are activated during the tilting. Those most readily activated would be perpendicular to the extensional component; however, if the antecedent fabric does not have a plane of weakness in this orientation, the most favorably inclined surfaces may be activated in preference to the development of new fractures. The northwest plunging folds may, therefore, be a direct secondary effect of the regional tilting.

These theoretical considerations indicate that the co-existence of two distinct northwest plunging fold trends in the Triassic rocks is explicable. Returning to Figure 68, it is evident that the more northerly trend dominates in areas A, B, possibly D, and E1-E2. It is also present in area C as the saddle described in the fold near Camp Indiandale; but it does not dominate the distribution of poles in this area, though it contributes to their scatter. Only in the eastern part of the quadrangle is the more westerly plunging E1-E3 trend dominant. In each case, the existence of the other trend is a plausible explanation for the considerable scatter from the main trend, but it cannot be established in the distribution. On the other hand, the interdomain axes of Figure 66 show no such geographic segregation. The conclusion is that both hypotheses, propounded to be consistent with the reality of two discrete fold trends, are partially correct. Subregions dominated by each of the two trends do exist, but the dominant trend of one persists into the other as a subordinate component.

The abrupt changes in width of the Triassic basin in the neighborhood of the Sinking Spring quadrangle obviously gives the structure of this area a unique character. Whether the type of folding with interpenetrating trends elucidated here persists on a regional basis, or is the effect of a transition between structural provinces of the basin, can be resolved only by investigation beyond the quadrangle limits.

Faulting

Even casual examination of the geologic map shows a profound difference in the structure of the Triassic rocks east and west of the Little Muddy Creek fault. To the west, mappable fault traces having the highest density encountered anywhere in the Triassic rocks of Pennsylvania have been mapped in detail. To the east, not a single fault is shown. This fact should not be construed to imply that absolutely no faults are present in the eastern part. Indeed, scattered occurrences of sheared and slickensided rocks are known, but no faults give mappable offsets of stratigraphic contacts nor persistently traceable concentrations of sheared fragments. Faults approximately parallel to bedding strike in the large, essentially homoclinal area would be particularly difficult to detect. Some such faults of appreciable displacement could be present in this area, but this fact does not alter the essential contrast between the east and west.

Intrabasinal faults in the western zone, while somewhat diverse in strike, evidently have attitudes more related to the trend of the basin than to the basement fractures considered responsible for the northwest plunging folds in the previous section. On the other hand, the surficial faults, with the possible exception of those with the greatest throw, may be entirely confined to the basin fill. While the Little Muddy Creek fault coincides with the boundary between the narrow, steeper dipping part of the basin and its wider eastern part for several miles, it may act in part as a surface of decoupling between these structural provinces. The particularly high concentration of faults westward from the Little Muddy Creek fault and extending into the narrowest part of the basin may reflect the accomodation of the basin fill to the change between the provinces.

Faulting at the northern margin of the basin is obvious west of the Little Muddy Creek fault for a number of miles, and its history appears to be unexpectedly complex. Some geometric and stratigraphic considerations argue that the border faulting should continue east of the Little Muddy Creek fault with increased displacement. McLaughlin concluded, with reservations, that such faulting was probably present although he did not show it on his map because convincing surficial evidence was entirely lacking. MacLachlan concludes that some faulting on this trend may have occurred before the diabase intrusion or may be entirely absent. He does require, however, that a substantial fault occurred somewhat south of the basin edge, east of the Little Muddy Creek fault to accomodate known fault displacements to the west; this would agree with the concept presented by others of step faulting and sedimentary overlaps at the northern margin of the basin.

Intrabasinal faults

The fault along the south foot of Laurel Ridge has been downthrown on the north side. Such a fault is denoted by the marked discordance between the strikes of the conglomerate on Laurel Ridge and the conglomerate members in the sandstones south of the ridge toward Reinholds. In the Womelsdorf quadrangle, this fault has downthrow on the south side, but only a few hundred feet from the quadrangle line it is joined by another fault that has downthrow on the north, and this approximately cancels out the displacement. Thus, the fault enters the Sinking Spring quadrangle with only a very small throw, which increases eastward. At the place where it terminates against one of the diagonal faults west of Vinemont, its displacement is calculated to be about 1,200 feet downward on the north side, relative to the rocks southwest of it. Slickensided rock occurs at a number of places along its course. Since there is clearly net downward displacement on the northern border fault along Laurel Ridge, the Laurel Ridge block effectively has a graben structure. However, there is some reason to believe that movement of the border fault was up on the southern side after the diabase intrusion. Since the fault south of Laurel Ridge apparently cuts a dike there is strong reason for supposing that this is a post-intrusive fault. If this is the case, then Laurel Ridge is, in fact, a step fault block rather than a graben.

Laurel Ridge itself and much of the hill area east of it are probably a single block, but near Fritztown the conglomerate is sliced by four faults that trend north northeastward, ending against the great border fault.

Downthrow of these four faults is on the southeast side. Though the area of conglomerate outcrop trends generally eastward, exposures in this area dip northwestward. Their strike is highly discordant with the trend of the ridge.

The easternmost of the four faults has the largest displacement. Its course is very close to the railroad line in the valley that trends south southwest from Fritztown. A heavily slickensided rock face is seen in an exposure along the railroad about 1,000 feet south of Fritztown. Conglomerate members east of the fault are truncated by it, and on the west side of the valley, directly on their strike, is sandstone that underlies the conglomerate of Laurel Ridge. The displacement on the fault is estimated at 700 or 800 feet.

Evidence of the next fault to the west is seen in a slickensided face on an outcrop along the telephone line about 1,000 feet west of Fritztown Road. The third fault to the west lies along a deep ravine that intersects the ridge and is indicated mainly by the areal distribution of sandstone and conglomerate, but some slickensided fragments were found. The westernmost fault also occupies a ravine.

A strike fault lies nearly parallel to, and north of, the railroad along Little Cocalico Creek from Reinholds northeastward and eastward to the bend of the railroad at Vinemont, from which point it continues eastward for nearly a mile, closely parallel to and south of the east-west portion of Shearer Road. Slickensided rock occurs at some places along its course, notably along the railroad about 1.5 miles northeast of Reinholds and in the ravine south of Shearer Road, about 0.5 mile west of Mail Route. At the latter place, abundant springs along the course of the fault are the sources of a tributary to Little Cocalico Creek. The part of the fault trace near Reinholds lies in the broad alluvium-covered valley of Little Cocalico Creek. Displacement on this fault is estimated at between 200 and 300 feet near Vinemont, but it may attain 700 feet or so near Reinholds. This figure depends on an adopted correlation of the conglomerate members north and south of the fault. Downthrow is on the south side.

Near Camp Indiandale, the common limb of the syncline and anticline is traversed by a fault which strikes northeasterly. Downthrow is on the north side. Where the fault crosses Mail Route, northwest of Mohns Hill, the calculated displacement is about 600 feet if the sandstone and conglomerate members are assumed to maintain uniform thicknesses. The displacement becomes less as the fault is followed southwestward. In the ravine east of Vinemont Road, the displacement is only 100 feet. At this place the fault branches. One branch trends slightly north of west, with downthrow still on the north side. It dies out near Indiandale Road. The other branch extends south of west, with downthrow at first on the *south* side, but this reverses near Indiandale Road, and west of there the downthrow is on the north. This branch cuts through the small dome of conglomerate west of Indiandale Road, where the throw is calculated to be about 150 feet. West of there it crosses the next north-south road and either dies out or continues with only small displacement until it meets the north-south fault a mile east of Reinholds.

The greatest displacement on this southern branch of the fault is at the point of the wedge between the two branches. There the rocks in the wedge are raised 450 feet relative to those south of them and 550 feet relative to those north of them. In this horstlike wedge, strata of the conglomerate member (I) dip westward 20° or more over a distance of several hundred feet, conspicuously discordant with the northward dip of the middle conglomerate member (II) only a few hundred feet to the north. This discordance is the clearest evidence for the northern branch of the fault, which traverses an area that is covered with brush and lacks outcrops.

Along the trace of the main fault east of its branching, and also along the southern branch, slickensided rock was found at several places, though not as abundantly as might be expected. The principal evidence for this fault is the truncation of conglomerate members that have been traced out. Where the fault branches, several springs in the deep ravine east of Vinemont Road are sources of the stream that flows northward from there. Along the southern branch of the fault, in a ravine about midway between Vinemont and Indiandale Roads, a fault surface is exposed in a small quarry. It probably represents a minor northward branch of the fault, for the slickensided face strikes N60°W and dips 42°SW.

Two north-south faults, in addition to the Little Muddy Creek fault, traverse the Newark rocks of this quadrangle. The westernmost extends along the valley of Little Cocalico Creek from near the southwest corner of the quadrangle, passes west of Reinholds, and continues for at least a mile farther north. It truncates and offsets several conglomerate members that have been traced to it from the east and west, but the amount of displacement is not clearly shown in this quadrangle, except near its northern end, where offsetting of conglomerate members indicates downthrow of about 200 feet on the east side. The throw is probably much greater near Reinholds, perhaps as much as 1,000 feet, if the conglomerate that passes south of the center of Reinholds is to be correlated with the member that comes from the west and is truncated by the fault about 0.3 mile west of the village. South of this quadrangle, the fault bends southwestward, following Little Cocalico Creek, traverses the northwest corner of the Terre Hill quadrangle, and passes into the Ephrata quadrangle, where it offsets the base of the Newark group north of Denver. There also the downthrow is on the east side, approximately 600 feet.

Another fault with strike north northwest to north enters the quadrangle south of Vera Cruz. It has downthrow on the west side and offsets several conglomerate members in the area east of Reinholds, as well as near Vera Cruz. The throw is calculated to be approximately 400 feet. This fault terminates to the north against the strike fault along the railroad.

Little Muddy Creek fault

The largest of the north-south faults follows the valley of Little Muddy Creek northward to the vicinity of Mohns Hill, where it bends northwestward and extends along the stream valley on the west side of Bran Road all the way to the north border east of Fritztown. That the displacement is to be measured in thousands of feet is plainly indicated by the fact that at the southern edge of the quadrangle the fault brings part of a very thick body of coarse cobble conglomerate on the east, against predominantly sandstone (with minor conglomerate), on the west. Diabase quickly intervenes on the west side of the fault, but the sediments of that area are chiefly sandstones, striking directly toward the higher parts of the thick cobble conglomerate. Along Bran Road, coarse cobble conglomerate on the west side of the fault adjoins diabase of the east side, and the intruded sediments there are sandstone with almost no conglomerate. Slickensided rock was noted at a few places along or near the fault, especially near U. S. Route 222 about 1,000 feet north of the southern edge of the quadrangle. Slickensided diabase was noted at a few places along Bran Road, but on the whole, shearing and slickensiding are surprisingly scarce, considering the magnitude of the fault. For over a mile west southwest of Mohns Hill, alluvium covers the fault trace along the valley of Little Muddy Creek.

The post-intrusive movement on the fault can be closely estimated with respect to the thickness of the diabase sheet. The latter figure contains the greater uncertainty. The northern lower margin of the diabase in the western block comes to the fault east of Mohns Hill. At this point the top of the sheet in the eastern block is calculated to be about 350 feet below the surface, assuming a dip of 15°. The dip value, suggested by the calculations of dip in the Colonial Hills area, is consistent with the inferred structure of the sheet and the width of the metamorphic zone. In any event, the point in question lies in the metamorphic zone and the error of the estimate seems unlikely to exceed +100 to –200 feet. Since the fault abuts against the north border, no significant component of strike-slip movement can be involved, and true throw will be equal to the depth of the upper contact to the east, plus the thickness of the plate. Using the extreme values of calculated thickness and probable error of burial estimates, the throw must fall in the range of 865 to 2,230 feet, and taking the preferred values, it is 1,550 feet.

On a stratigraphic basis, McLaughlin computes about 3,600 to 5,600 feet of displacement close to the point where the above determination was made. It is obvious that approximately half or more of the displacement occurred prior to the intrusion. Indeed, if Hotz (1952) is correct that space for diabase emplacement was obtained by lifting the roof, then the displacements calculated by McLaughlin below must be increased by the thickness of the sheet, as the areas compared lie above and below it.

The conglomerate of Laurel Ridge and the hills southeast of Fritztown is believed to be roughly the stratigraphic equivalent of the lower part of the large body of conglomerate in the southeast corner of the quadrangle. The indicated lateral offset is approximately 2.5 miles, for an average dip of 30°. This calculation corresponds to more than 6,000 feet vertical displacement. This calculation is an oversimplification and may be misleading. The conglomerate in the southeast corner has a purely homoclinal structure, while the rocks west of the fault are folded in the area about Camp Indiandale, and the plunging folds are cut off by the fault.

Precise equivalence of conglomerates east and west of the fault is difficult to establish. One possible correlation would make the lowest thick conglomerate (I) near Camp Indiandale equivalent to the lowest beds of conglomerate just south of the southeast corner of this quadrangle. If this is correct, then the stratigraphic throw is approximately 1,500 feet at the southern edge of the quadrangle. At 1.2 miles farther north, the strike of the base of conglomerate II runs toward the thick sandstone member in the conglomerate east of the fault. These two horizons are respectively 560 and 3,050 feet above the adopted base of the conglomerate series. The throw is the difference, or 2,490 feet. At 0.6 mile farther north, the strike of the base of conglomerate II on the north limb of the syncline runs directly toward the top of the conglomerate series east of the fault. These horizons are respectively 560 and 4,140 feet above the conglomerate base, and the throw is therefore 3,580 feet. To the north the diabase intervenes and structure renders further calculations impractical. The displacement may well decrease along the northwestern segment of the fault as dips on the east are persistently less than on the west.

The other most probable correlation of conglomerates would make the lowest cobble conglomerate south of the southeast corner equivalent of the base of the Laurel Ridge conglomerate and its eastward extension near Fritztown. If this is correct, then all the displacements mentioned in the preceding paragraph must be greater by about 2,000 feet.

About 200 yards south of the quadrangle boundary near Adamstown, the Little Muddy Creek fault terminates against a major fault trending south southwestward through Adamstown and Swartzville to Reamstown and the Lancaster Valley at the south side of the basin. Major movement on this fault to the southwest evidently passed onto the Little Muddy Creek fault as its northeastward continuation is not apparent in the Sinking Spring quadrangle. This fault is mapped by Jonas and Stose (1926) in their New Holland quadrangle report and by McLaughlin on a map of the Terre Hill quadrangle in the Pennsylvania Geological Survey files. Neither worker assigned a name for this feature, but it is provisionally designated the Swartzville fault here for convenience in reference. Near the junction, McLaughlin calculated 1,500 (or 3,500) feet of offset of conglomerate beds to which should probably be added about 1,200 feet of elevation by diabase intrusion to obtain the total fault displacement yielding 2,700 (or 4,700) feet. The displacement increases northward to the vicinity of Mohns Hill to 4,780 (or 6,780) feet allowing for the diabase intrusion. Of this displacement about 1,500 feet followed the diabase intrusion near Mohns Hill, and this cannot decrease much northward to the border. In the absence of any contrary evidence, it is considered probable that the late displacement is approximately uniform along the Little Muddy Creek fault trace and is taken up at either end by border faulting and the Swartzville fault.

The Little Muddy Creek-Swartzville fault system is the only transverse fault known to cut completely across the Newark-Gettysburg basin, and it probably has a greater displacement than any other fault having Triassic rocks on both sides. The association of this fault system with the abrupt decrease in the basin width seems highly significant. While regional fold trends persist across the fault, a considerable area in the neighborhood of Camp Indiandale was deformed independently on opposite sides of the fault. While the persistently steepest dips of the basin neck are attained only west of the Sinking Spring quadrangle, the trend becomes evident immediately west of the fault. The great movement on the Little Muddy Creek fault obviously requires corresponding adjustment on the northern edge of the basin, but locating those adjustments has proven difficult.

The North Border fault

Some years ago, a favored interpretation of the northern edge of the Newark basin postulated a continuous series of faults along the border. However, a great deal of evidence now shows that, at some places, the Newark rocks at the north border lie unconformably upon or against the older rocks exposed to the north. Some of these localities were described many years ago by Wherry (1913), and the present author fully confirms his interpretations (McLaughlin, 1961). Mere juxtaposition of pre-Triassic rocks and rocks high in the Triassic column is not necessarily an indication of a profound post-Newark fault. The Newark rocks may well have been deposited against steep mountain slopes produced either by erosion or by faulting that preceded deposition.

In the Sinking Spring quadrangle, the evidence very clearly requires a major fault along the north border west of Bran Road. In the adjacent Womelsdorf quadrangle, shearing and brecciation are evident at several places near the contact. These indications continue into the Sinking Spring quadrangle. Exposures along the road at the north foot of Laurel Ridge near the golf course are heavily sheared. The moderately steep southward dip of these rocks, contrasting with the northerly dips on the crest of the ridge, are interpreted as drag. The lack of any identified Precambrian or Cambrian pebbles in the conglomerates of Laurel Ridge likewise demands a considerable displacement here. The maximum net displacement inferred by McLaughlin (1958) in the Womelsdorf quadrangle is about 7,000 feet. This decreases eastward, and it may be as small as 2,000 feet along the north foot of Laurel Ridge. It may decrease a little toward Fritztown, in the area where the diagonal faults slice the conglomerate, or it may remain nearly the same as far as Bran Road.

At Bran Road, the Little Muddy Creek fault reaches the border. The downthrow on the east side of that fault is calculated to be at least 4,800 feet at Mohns Hill (see above). Thus, to the estimated 2,000 feet displacement on the border fault, we add 4,800 feet or a greater amount, if we adopt an alternative correlation of conglomerate members. Of this displacement, about 1,500 feet is post-intrusive displacement, which cuts the Morgantown sheet all the way to the border and cannot be accommodated by some fault hypothicated to lie south of the border. The obvious explanation is that the border fault continues east of Bran Road with increased displacement; however, there is no clear evidence of such continuation, but there are several indications that this is not a locus of major faulting.

West of Bran Road, the trace of the border fault is clearly defined by a deep valley in which sheared or slickensided debris is fairly abundant. To the east for a short distance, the Triassic border abuts colluvium-mantled Paleozoic limestones and no surface expression of possible faulting need be anticipated. It should be evident between the quartzite of Grings Hill and the Triassic rocks. There is indeed a valley along Gelsinger Road following this trace. Slope debris from both sides obscures exposure in the neighborhood of the projected fault; but it is noteworthy that sheared or slickensided fragments are not known and the valley is much less pronounced than west of Fritztown. These are significant facts if this valley is actually the trace of a fault having more than twice the displacement of the fault so clearly defined to the west. The thickness of the diabase exposed between Gelsinger Road and the Wheatfield area was calculated to be 712 feet. This is at the extreme lower limit of the possible thickness range calculated for the sheet as a whole. This fact might imply some faulting at the north margin of the diabase; but in view of the fact that this segment lies in atypical country rock and almost certainly near the original northwestern limit of intrusion, the low thickness may represent a complete diabase section. The mineralogy of the Hardyston Formation is such that it should be fairly insensitive to thermal effects of the diabase intrusion. Some such effect may be indicated, however, in the small quarry near the west end of Gelsinger Road. If this is correct, little or no post-intrusion faulting is indicated between this exposure and the Morgantown sheet. Exposure conditions obscure evaluation of thermal effects elsewhere. If faulting is present at the Triassic border east of Bran Road, it must, in any event, die out quite rapidly along strike for so large a displacement, as the border is clearly an unconformable overlap a few miles east at the Schuylkill River.

In the Wheatfield area, immediately south of the diabase along Gelsinger Road, Triassic sediments rest unconformably on Paleozoic carbonate and shale. This fact alone does not necessarily preclude substantial faulting between the Wheatfield area and Grings Hill, as the Paleozoic rock might be deduced to come from high in cover present above the quartzite and gneiss during the Triassic. However, this does not seem to be the case. Poor exposure and metamorphism of rocks in the Wheatfield area make stratigraphic identification difficult. MacLachlan judges that the carbonates are very probably Cambrian in character of the non-carbonate constituents, probably Millbach or Buffalo Springs Formations on the basis of color; though the latter properly may be a result of metamorphism. The shale is to be identified with the Martinsburg Formation almost as surely as that in other exposures isolated from the main shale belt. Martinsburg shale overlying Cambrian limestone is known at only four other places in eastern Lebanon and Berks Counties: The low ridge north and northwest of the city of Reading, at Shillington, *underneath* Grings Hill as shown by exposures near either end, and at Kleinfeltersville. In each case, the Martinsburg owes its position to thrusting which in turn emplaces older rock above the Martinsburg. While MacLachlan thinks it probable that thrusting (Neversink thrust ?) may formerly have extended above Grings Hill, he doubts that on a regional and theoretical basis a repetition of thrusting with shale over Cambrian limestone is credible. In any case, shale is known to overlie Cambrian limestone north of the border less than a half mile from where the same relationship may be observed in the Wheatfield area. In the absence of suspected faulting, there would be no question that these occurrences should be taken to represent the same tectonic horizon. In view of the lack of concrete evidence for the suspected fault, this fact alone is considered sufficient reason to suggest that faulting of the required net displacement is not present at the north margin of the Triassic rock in this area.

Exposure of rocks underlying Grings Hill in the Wheatfield area may, in fact, require some elevation with respect to the rock north of the border, but not more than may be accomplished by intrusion of the diabase without recourse to faulting. Taken back to the depositional environment, the situation is more problematical. Would the overlapping Triassic sediments have formed with the observed lithologies if the Paleozoic rocks of the Wheatfield area were approximately in their present position with respect to the quartzite of Grings Hill at the time of deposition? In a somewhat analoguous situation north of Cocalico in the Womelsdorf quadrangle, MacLachlan judges that the answer is no. In the Cocalico area, it appears that a complex extended history of up and down movements between the shale of the exposed pre-Triassic basement and adjacent gneiss of South Mountain, is required to explain all features. Constraints of space and lithology are not as severe in the Wheatfield area, but the same kind of questions arise. If the Wheatfield situation is legitimately comparable to the Cocalico situation, then faulting between Grings Hill and the Wheatfield area is indicated. Net displacement of such faulting could be either up or down on the Wheatfield side, but it would clearly not be of the magnitude required to absorb the combined displacement of the border fault west of Bran Road and the Little Muddy Creek fault.

Any faulting required to achieve the correct depositional environment in the Wheatfield area would precede diabase intrusion. The absence of surficial evidence of such faulting may then be quite reasonably explained by postulating that intrusion of this part of the sheet was actually controlled by the fault surface. Near Grings Hill Road the diabase swings southeastward away from the border. The contact between Triassic sediments and the Hardyston Formation in this area is buried in quartzite colluvium, and there is no prospect of detecting any possible faulting, though the faulting may have taken place there.

The preceding catalog of perplexities and possibilities may leave room for argument, but it is believed the weight of the evidence justifies the following conclusions. 1) There is probably no faulting on the Triassic border east of Bran Road after the diabase intrusion. If there is any such faulting of this locus and age, it is not of sufficient magnitude to accommodate known post-intrusive movement on the Little Muddy Creek fault. 2) Net cumulative throw on faulting, if any, at the Triassic border east of Bran Road cannot exceed several hundred feet. This is too small to accommodate the combined displacement of border faulting west of Bran Road and the Little Muddy Creek fault by a whole order of magnitude.

The consequences of these conclusions imply unexpected complexity of the structure of the north border. Since post-intrusive movement on the Little Muddy Creek fault clearly extends all the way to the north border, if this displacement cannot be accommodated at the border by down faulting the Triassic east of Bran Road, it must be accommodated by up faulting the Triassic west of Bran Road. The conclusion that there is an up faulting phase of movement on the established border fault is contrary to traditional interpretations, but it is reconcilable with a north-south compressional component involved in the regional tilting. It also provided a good explanation for the intrabasinal faults near Laurel Ridge. The fault south of Laurel Ridge has post-intrusive movement and is down to the north. Toward the east end of Laurel Ridge, four faults are all progressively stepped down to the east. Other explanations for these displacements individually may be adequate; but general uplift, with some marginal steps of the area south of the border and west of the Little Muddy Creek fault gives a consistent pattern of movement.

While there is substantial reason for believing that late movements elevated the Triassic sediments, there is no reason to doubt that net displacement of the border fault west of Bran Road is the previously indicated 2,000 feet down to the south. The late movement must simply be added to the net displacement to obtain a larger initial down faulting.

The problem of accommodating the major displacements is unchanged. Pre-Triassic basement west of the Little Muddy Creek fault is depressed about 2,000 feet by faulting below the Paleozoic rocks to the north; east of the fault, near Mohns Hill, pre-Triassic basement is depressed at least 4,800 feet by faulting below basement to the west. It follows that a fault of very large displacement must exist between Mohns Hill Road and Gelsinger Road. If such a fault cannot be located north of the Wheatfield carbonate area, it must lie to the south.

Given the necessity for locating such a fault, certain features in the Sinking Spring quadrangle and more positive indications to the east in the Reading quadrangle point to its location, though its trace has not been identified by field criteria. From the east border of the Sinking Spring quadrangle, the crop of the Morgantown diabase sheet runs due east for about 2.4 miles and then east northeasterly for 2 miles. Throughout this span, the diabase is shown to have a very steep dip by the symmetric magnetic pattern, the relatively narrow crop width, and the rectilinear contacts uninfluenced by topography. The abundance and distribution of conglomerate members on either side of the diabase differ to a degree which cannot be reconciled with the present interval between them. The trace separates areas with strongly different bedding attitudes as reflected in Figure 66. The obvious conclusion is that this segment of the diabase is intruded in a substantial fault.

This faulting might end east of Colonial Hills where the diabase swings northward and dips southwest at a low to moderate angle. Several features point to its continuation, though no explanation for departure of the intrusion from the fault, presuming continuation, is known.

The very irregular contact of the diabase in the immediate vicinity of Colonial Hills, if examined in detail, will be seen to be inconsistent with any simple configuration of the diabase surface. It may be readily explained by supposing that several small tongues of diabase project from the main mass only in this particular area. Such a local peculiarity might well represent injection of diabase tongues into the shatter zone of the fault.

Just west of the diabase at Colonial Hills, a few conglomerate beds have attitudes conspicuously different from those uniformly prevailing elsewhere throughout the terrane east of the Little Muddy Creek fault and south of the diabase. Ill-defined contacts suggest that these beds might wrap around a fold hinge into the general attitude, but a paradox ensues. Dips in the north limb of this supposed fold are both smaller and more irregular than in the south limb. It follows that the north limb should be somewhat wider than the south limb. In fact, the opposite is true by a conspicuous margin. Other explanations for this relationship can be contrived, but fault juxtaposition of different conglomerate members is sufficient.

Continuing the trend westward is the prominent magnetic high near the intersection of Chapel Hill Road and Goose Lane. In a previous section it was noted that this seems to represent a localized excess thickness (that is, downward projection) of the diabase. It was also observed that this magnetic high lay on the trend of several small diabase bodies apparently intruded in a fracture or shatter zone associated with the Little Muddy Creek fault. If this feature, in fact, lies at the intersection of a shatter zone with a major fault, a localized thickening of the diabase is not surprising. It may even be the site of a true feeder pipe. The shape of the magnetic anomaly is consistent with a cylindrical body plunging steeply southeast. This is the direction expected for the plunge of the proposed fault intersection if both faults are normal.

Finally, the projected fault trace reaches the Little Muddy Creek fault exactly at the sharp bend from northerly to northwesterly. This abrupt deflection of the Little Muddy Creek trace does not require conjunct faulting, but it is mechanically reasonable.

The proposed fault crosses the contact of Morgantown sheet at Colonial Hills and again east of Chapel Hill Road. At Colonial Hills, irregularities in the contact make it impossible to be certain whether it is offset, but the amount of possible displacement is very small. There is evidently no offset of the contact near Chapel Hill Road. It is, therefore, concluded that movement on this fault entirely preceded intrusion of the diabase.

None of the above considerations individually compels adoption of the hypothesis of westward extension of the fault in the Reading quadrangle. Their collective alignment, however, seems sufficient reason for assuming this extension even in the absence of *a priori* reasons for anticipating a fault in this vicinity. Given both the geometric necessity of producing space by faulting and consistent local clues to its presence, this fault is considered to be as well established as is possible for any which has not been directly observed.

The preceding movements on faults at or near the north border of the Triassic basin may be sufficient to explain all observed relationships in the Sinking Spring quadrangle. An additional complication must be introduced to fully explain features of the border in the Womelsdorf quadrangle. Details and supporting evidence require too much space to present here and will be reported in a separate paper (MacLachlan, in preparation). The essential conclusions are that the shale area north of Cocalico and south of the border fault is presently uplifted with respect to its tectonostratigraphic position below the thrust sheet immediately adjacent to the north; furthermore, sedimentological considerations demand that it be at least a few hundred feet, and probably more than 1,000 feet, more elevated with respect to South Mountain at the time of deposition. Demonstrable downthrow of the southern block subsequent to deposition was previously calculated by McLaughlin (Geyer and others, 1963) to be sufficient to explain the difference. Eastward from Cocalico, the net cumulative displacement is downward on the basin side and positive proof that an initial uplift is lacking. It was previously noted that comparable faulting between the Wheatfield area and Grings Hill would make for more comfortable interpretation of the Wheatfield area though it may not be essential. Continuity of such faulting from the west end of South Mountain, near Cocalico, to the Schuylkill River or beyond, would actually simplify some aspects of regional structure. In this case, some down faulting of the basin along Gelsinger Road would be definitely implied, but all such movement would be older than the diabase intrusion. It could also be older than the limestone conglomerates forming an overlap contact at the Schuylkill River, which are apparently much higher in the stratigraphic section than the Hammer Creek beds exposed at the border east of Bran Road. The movement would clearly be subsequent to the deposition of the latter beds.

The presence of some downward faulting along Gelsinger Road prior to the diabase intrusion, however, in no manner negates any relevant part of the argument requiring a fault south of the Wheatfield area. Downward movement along the Gelsinger Road trace would merely bring the predepositional surface of the basin down to its observed position in the

Wheatfield area. It would, in no case, account for the additional depression of the pre-Triassic surface indicated south of the Wheatfield area. It does indicate that downward displacement of the border fault west of Bran Road might be distributed on faults north and south of the Wheatfield area.

The implication of this proposed fault is that rock of the structural level of the Grings Hill thrust plate (that is, South Mountain, etc.) and higher is either not present or very thin in the pre-Triassic basement of the Newark-Gettysburg basin. Considering the fact that known areas of unconformable overlap of Triassic sediment largely expose pre-Triassic rocks not far removed from the Grings Hill level, absence of the Hardyston Formation and Precambrian gneiss makes interpretation of Hammer Creek petrography simpler.

Probable late uplift of the basin at its north margin, amounting to a fraction of previous depression is indicated west of the Little Muddy Creek fault. This movement was judged to be consistent with the mechanics of basin deformation. On the other hand, there seems to be no obvious direct mechanical connection between the proposed initial uplift and subsequent Triassic history, except the planes of weakness imposed on the structural grain.

Given the time limits of possible faulting, after D_2 (Alleghanian) folding and thrusting and before Upper Triassic sedimentation, uplift of an area south of the Great Valley is most reconcilable with compressional tectonics of the Alleghanian. This implies a high-angle reverse fault or steep thrust, though a strike slip component cannot be excluded. It might by hypothesized that the movement may be related to the Cornwall-Kelvin lineament of Woodward and Drake (1963) ; though MacLachlan believes that any net strike slip parallel to the Triassic basin between the Susquehanna and Schuylkill Rivers must be in the opposite sense to that proposed by Woodward and Drake, on the basis of facies of Lower Paleozoic rocks and probable tectonic provenance of Paleozoic nappes. The development of the reverse fault is mechanically consistent with D_3 cleavage and crenulation in Paleozoic rocks in the Sinking Spring quadrangle.

MINERAL RESOURCES AND ENVIRONMENTAL GEOLOGY

by D. B. MacLachlan

LIMESTONE AND DOLOMITE

All carbonate formations have been locally quarried for agricultural lime; and larger quarries were developed for metallurgical flux in both the Beekmantown and Conococheague Groups during the period of local iron making. No substantial body of stone meets modern metallurgical requirements nor the modern requirements for any other use where composition is critical, except possibly as a component for cement manufacture.

Rocks of this type are the usual preference for concrete aggregate and other crushed stone uses in this area. Commercially acceptable crushed stone is produced from the Allentown Formation near Reading, but the heavily bedded limestones and dolomites of the Beekmantown Group should be a more consistently reliable source. The Epler Formation is presently being quarried by E. J. Brenneman Inc., near Cacoosing. The dolomites of the Ontelaunee Formation have prospects for producing an even tougher aggregate, though cherty rock near the base of the formation should be avoided for use in concrete (and to prevent undue wear of crushing machinery). With the exception of the chert zone in the Ontelaunee Formation in the vicinity of the contact with the Epler Formation, there are no present indications that any particular horizon or zone in the Beekmantown Group is particularly suitable or unsuitable for crushed stone production. There are abundant reserves to meet present demands; but, in view of the fact that urban development is spreading most conspicuously along the limestone valley north and west of Reading, municipal officials and regional planners should take steps to make certain that some areas suitable for quarrying are set aside for that purpose within a reasonable distance of the market, as transportation costs are commonly a significant portion of the cost of delivered stone.

The Hershey Formation of this quadrangle, in most respects, is very similar to the cement rock of the Jacksonburg Formation. The rock, however, is usually too magnesian for cement manufacture and seems to have no economic potential at this time. Some chemical analyses of these rocks and other rocks in the area are included in the Appendix.

Although much has been written about the groundwater and soil of a limestone terrane, as well as the importance of limestone and dolomite as a valuable mineral resource, very little information is available on the hazards present in carbonate rocks. These hazards occur because carbonate rocks are subject to solution on the surface and in the subsurface, with the development of caves and sinkholes. Figure 69 shows a diagrammatic cross section through an area with solution of the carbonate bedrock.

The sketch shows pinnacles or jagged and roughly weathered edges as opposed to a smooth surface on top of the bedrock. When the overlying soil and unconsolidated material dry out, downward migration of soil debris into solution cavities takes place. The arch over the solution opening tends to migrate upward as material gradually falls into the opening. Collapse may occur when unusually heavy load conditions exist over the

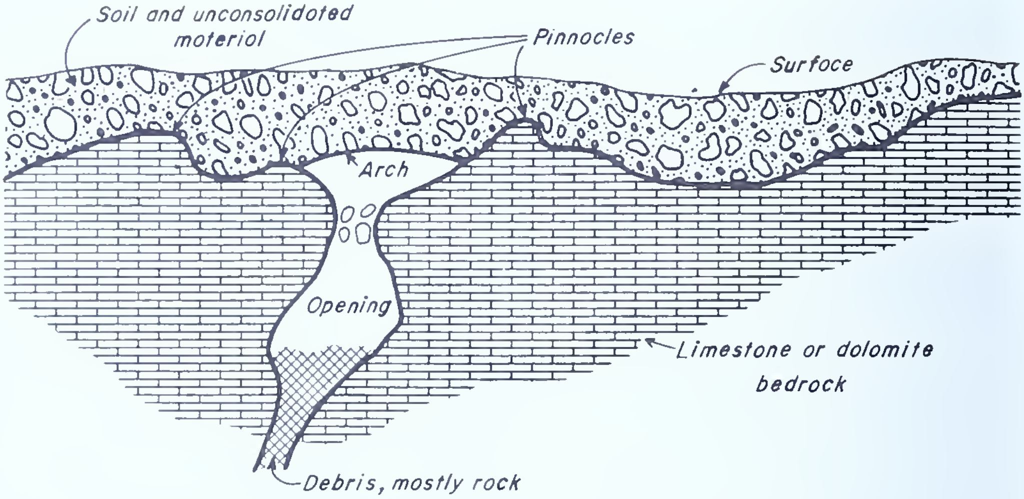

Soil and unconsolidated material
Pinnacles
Surface
Arch
Opening
Limestone or dolomite bedrock
Debris, mostly rock

Figure 69. Hypothetical cross section through sinkhole.

arch, causing the arch to break. A heavy rainstorm that saturates the soil and weakens the arch may act as the trigger for collapse. A catastrophic type of collapse can occur above the area of pinnacles or jagged bedrock, whereas a general subsidence is likely over areas of a smooth-surfaced bedrock. Sinkholes of the catastrophic type are usually steep or vertically walled and may range from 5 to 10 feet to in excess of 100 feet deep.

Areas in danger of collapse by sinkhole development are extremely important in considering the foundation requirements for highways, dams, bridges and high-rise buildings. As the population increases and shifts to suburban districts, more of the carbonate bedrock area will be the site of extensive road building, industrial development and private housing expansion. It is important to be aware of the potential hazards present in these carbonate rocks in order that proper testing and planning will precede construction.

Other engineering difficulties encountered with the carbonate rocks are not severe. The Beekmantown and Conococheague Groups generally stand well in vertical cuts as may be seen in quarries, some more than a hundred years old. There is some hazard of individual blocks falling, especially during spring thaw. A special program may be encountered where the beds dip into the cut as shown in Figure 70. In this case, it may be necessary to anchor the rock to prevent slip on the bedding planes. It is recommended practice in highway construction to remove rock back to the dip of the beds where they dip directly toward the cut at an appreciable angle. Thin-bedded and argillaceous limestones of the Myerstown and Hershey Formations stand adequately in excavations but should be cut back 2 on 1 for permanent cuts.

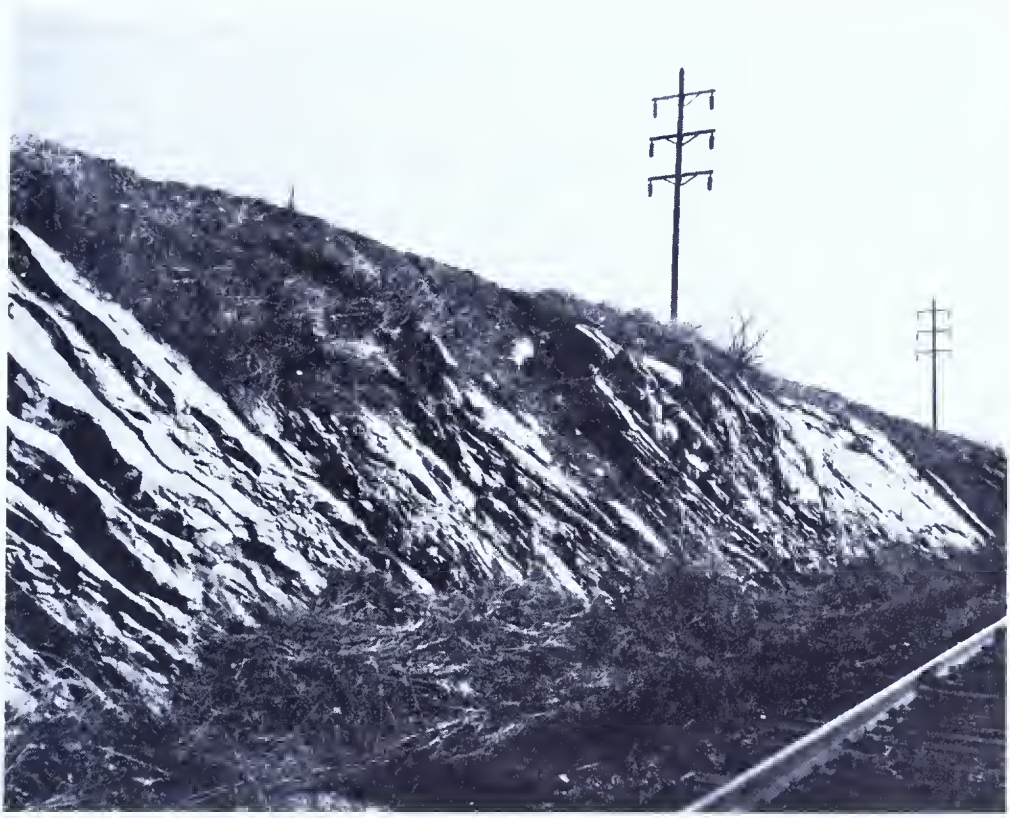


Figure 70. Dip slope cut in Richland Formation. Note use of rock bolts to prevent displacement of slabs down bedding surface.

SHALE AND CLAY

Shale for brick manufacture is presently produced by the Glen Gery Shale Brick Company from a quarry (Figure 71) southeast of State Hill for use as a blending ingredient in their Reading plant. Shale suitable for brick and other heavy clay products is also available elsewhere in the area where Martinsburg shales of lithic types 2 and 5 occur, on the basis of tests reported from the "Martinsburg Formation," O'Neill and others (1965). Many areas of the "Martinsburg Formation" prove to have good to excellent potential for use in the manufacture of light-weight aggregate. This material has not been produced in this area, but it is of increasing interest for use in reinforced concrete construction. Lapham and Hoover (1971) report that "Martinsburg Formation" shales, in a belt evidently extending into the Sinking Spring quadrangle, often exceed 20 percent Al_2O_3 and have future potential as a low-grade aluminum ore. It should be anticipated that if material of this grade is to be employed for aluminum manufacture, sources closer to supplies of cheap electric power will be preferred, if available.

Indications of a deposit of white clay, presumably derived as residual material from the Jacksonburg Formation, was encountered in mapping the valley about two miles east of Brownsville. Somewhat more than a foot of this clay was found above water level in the bank of a stream, and similar material had been mixed with soil by cultivation, for several hundred yards to the southeast. Results of analysis and use tests of this material are reported in the Appendix.

The shales generally make good foundation material but tend to be unstable in cuts on exposure of several years. They should ordinarily be taken to about 2 on 1 in cuts. The purple and green shales of lithic type 5 are more resistant and may be allowed to stand steeper. The shales are commonly weathered to appreciable depth and residential excavations can be made with a backhoe or comparable equipment. Fresh rock can usually be ripped without blasting, but heavy equipment will be required.

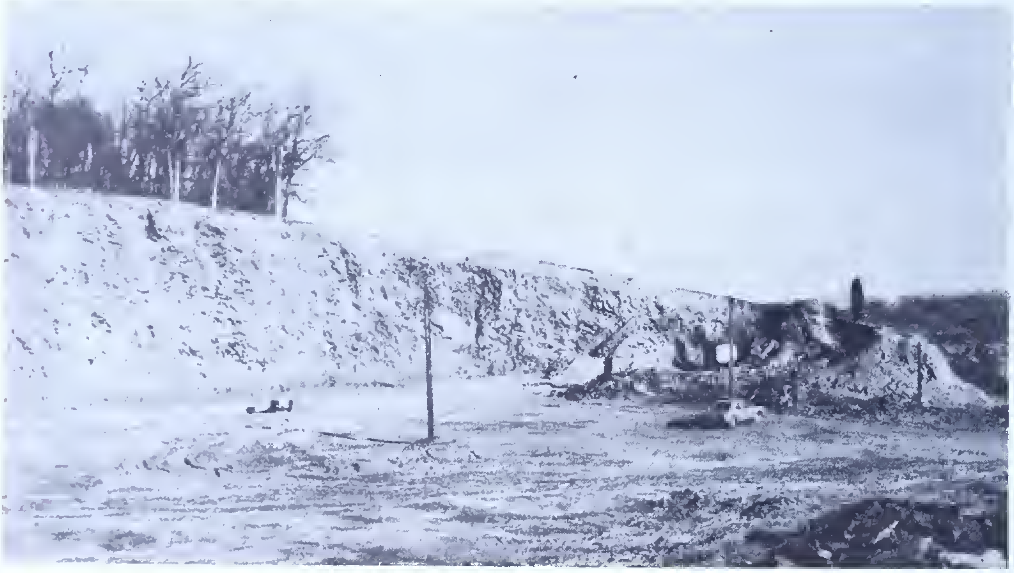


Figure 71. Brick shale quarry southeast of State Hill. Shale appears to be somewhat weathered through the whole depth of the cut.

SAND AND GRAVEL

Construction sand is produced at Grings Quarry from weathered surficial material of the Hardyston Formation. This is one of the few sources of sand in the neighborhood of Reading. Other areas of suitable deeply weathered Hardyston Formation can probably be developed. Large quarries on the north slope of Grings Hill were formerly worked for ganister and silica brick manufacture. Substantial reserves of suitable material are probably available if it should ever again be in substantial demand, but different refractories are commonly employed in modern steel making practices.

Sand and gravel have not been produced from unconsolidated surficial deposits in this area. Alluvial deposits are not substantial and are not known to contain any significant lenses of reasonably clean material in the coarser grades. The quartzite colluvium of the Hardyston Formation, however, may have some potential as a gravel source. There is a major fraction of admixed finer material, but it would be amenable to production of a clean product by a simple dry screening process. If reasonable care is taken in planning of the operation and return of the fine screenings, the gravel fraction could be recovered with little permanent effect on subsequent land use.

TRAP ROCK

Diabase has not been quarried in or near the Sinking Spring quadrangle, owing to an abundant supply of limestone, which may be extracted at somewhat less expense. In many areas, trap rock is the preferred material for concrete aggregate, road base, railway ballast, and general crushed stone uses owing to its extreme toughness and durability. In both these properties, and probably in skid resistance on highway surfaces, it is superior to limestone and dolomite. Large reserves of this material are available in the Morgantown diabase sheet should a demand for it develop. In view of the fact that land underlain by diabase is generally hilly, has poor stony soil and poor water supply, it is not suitable for most agricultural, residential or industrial purposes. As the exact opposite is true of the limestone areas, it may eventually develop that with probable increasing urbanization, it may be economic to produce trap rock, even at greater extraction cost, as quarry sites reasonably close to the major markets can be obtained at reasonable cost and could have an advantage in shipping cost.

HIGHWAY SURFACE MATERIALS

Recently adopted highway department specifications require the use of skid resistant aggregate in surface courses. In addition to possible use of trap rock previously mentioned, crushed quartzite from below the weathered zone of the Hardyston Formation such as obtained from the deeper levels of Grings quarry may potentially be suitable for this use. An additional material which has previously been considered to have no economic use is sandy hornfels from the metamorphic zone of the Hammer Creek Formation. Preliminary indications are that this rock may be particularly adapted to this use. All three of these rock types are abundant in the area and underlie infertile hill land. Reserves appear to be essentially unlimited and future availability seems to be only slightly affected by conflicting land use.

BUILDING STONE

Modern building practice is such that stone is required occasionally for ornamental purposes or to maintain architectural integrity. Limestone, quartzite, gneiss, and brown sandstone, both as rough field stone and dressed, have been used in construction of older buildings in the area. If the expense is warranted and material needed for restoration or harmonious new construction, these materials remain available. In the absence of a continuing market, the expense of opening a small quarry for any particular project must be anticipated. If limestone is required, the operator should avoid dolomite which weathers with a yellowish color and would probably be objectionable for most uses.

Two possible commercial building stone opportunities do exist in the area. The diabase of the Morgantown sheet is the type of rock presently produced and marketed as black granite for ornamental and monumental uses. The coarse-grained phase abundantly distributed in this area, as shown in Figure 63, may be interesting for this use. The Hammer Creek standstone between conglomerate I and II of the Camp Indiandale area (Figure 62) appears to be a high grade of the traditonal brownstone once widely used. It is conceivable that a fashion whim might give rise to some demand for this stone, but even failing this possibility, a small continuing demand from a wide area might be established for repairs and additions to the many existing structures of this stone.

IRON

Iron ores were formerly produced in the Sinking Spring quadrangle to supply local furnaces in this area and Reading during the nineteenth century. Brown ores (limonite) formed in patchy residual deposits on the limestone were apparently worked in a number of places, in some cases, perhaps for barn paint pigment rather than smelting. The largest operation was apparently the pits north of the railroad just west of Wernersville. No ore was observed on the surface here, but nodular masses of limonite are occasionally found scattered in the fields. The most abundant material was found north of Little Cacoosing Creek about one mile northeast of Wernersville though there is no known history of mining there. Ores of this type are not considered very desirable in modern steel making practice, and modern mining and marketing conditions are such that there is no possibility that a sufficiently large deposit having any economic value exists in this area.

Magnetite iron was produced as recently as 1905 or 1906 in the Wheatfield Mines about two miles east of Fritztown. This is a small deposit formed by replacement of limestone adjacent to the large diabase intrusion. The ores are similar in mineralogy and genesis to those at Cornwall (Spencer, 1908) and Morgantown (Sims, 1968). Unlike the great volumes of ore in those notable mines, however, "The ores occur as irregular masses, having a general layer-like form, interbedded with the limestone strata, but the ore bodies are numerous rather than large, and lack of persistence is a marked characteristic" (Spencer, 1908). High sulfur and relatively low iron content of the ores as well as the irregularity of the deposits were apparently the reason for abandonment. Some ore was known to have been left in the ground. A small distinct magnetic anomaly is undoubtedly associated with this ore. The size of the anomaly does not suggest any significant quantity. It remains, however, the best mineral prospect in the Sinking Spring quadrangle. In the unlikely event that sufficient ore should remain, modern milling techniques can produce a high quality concentrate from this ore with possible byproduct value. If ore were recovered, suitable concentrating plants presently exist at Cornwall and Morgantown.

Location of the old workings in the Wheatfield area, as indicated by Spencer (1908), are shown on Plate 2. Some of these workings were difficult to locate in 1965 and the area has recently been much disturbed by sanitary landfill operations.

OTHER METALS

There is no known production of any metal other than iron in the Sinking Spring quadrangle. D'Invilliers (1883) reports analyses and descriptions of ores from the Wheatfield district which show them to be comparable to the Cornwall and Morgantown ores with some copper content. There is no indication that any copper was recovered during the working of these mines; but, if a workable body of magnetite ore should be encountered in this area, some copper by-product value might be anticipated with modern processing techniques. Even smaller values of silver, gold, and possibly cobalt might be obtained, though it seems likely that even under the most favorable circumstances the total recovery of the latter materials would be trivial. Present indications are that no area in the quadrangle, except the Wheatfield district, shows any potential prospect of metal production.

A trace element survey of stream deposits in southeastern Pennsylvania (Keith and others, 1967) shows a low copper anomaly associated with Cacoosing Creek drainage and a moderate copper and zinc anomaly associated with Spring Creek drainage. This study does not pursue the question of the origin of such anomalies at any length, but it is explicitly stated that they are not necessarily associated with any economic concentrations of metallic minerals. Continuing analysis of the data of Keith and others, Penn State University (1970), which has not been reported in detail, relates trace element abundances to iron and manganese concentrations. According to the theory of this procedure, trace element abundances are considered truly anomalous only if they deviate significantly from iron and manganese measurements. By this criterion, the zinc anomaly in the Spring Creek basin is not indicative of a significant concentration according to a map given with the 1970 note. No analysis of the copper anomalies has been presented, but several comments are appropriate. The Cacoosing Creek drainage includes the Wheatfield area and no other apparent source of excess copper. It seems plausible that the modest copper indications in this stream could be wholly derived from leaching of chalcopyrite associated with the Wheatfield mineralization. The Spring Creek basin has a really significant copper concentration at only one of seven sampling localities. This occurrence is located southwest of Robesonia, near the north edge of South Mountain and lies outside the Sinking Spring quadrangle. The source of the copper is unknown; there is a remote possibility that it might reflect a mineral concentration, but the single occurrence would suggest that it is not sufficient volumetrically to represent an economic potential.

GROUNDWATER

A detailed study of the groudwater resources of Berks County is currently in progress, and any attempt at detailed evaluation of groundwater supplies in the Sinking Spring quadrangle would be premature. General groundwater conditions in the various lithologic units are shown on the legend of the geologic map as interpreted from regional studies and reports of other areas of apparently similar lithology. A few general remarks based on studies outside the quadrangle which may be helpful are given below.

Hardyston Formation, Gneiss and Diabase

These rocks are all poor aquifers and may fail even domestic supplies. In a couple of occasions on South Mountain, adequate supplies have been obtained as much as half a mile from the northern border by drilling through the thrust plate into the underlying carbonate rock. The same technique might also be effective near the north edge of the gently dipping part of the diabase sheet north of Colonial Hills. It is not certain that the underlying metamorphosed sediments would give appreciably better yield in this case. The depths required and the costs of drilling in these tough rocks are such as to put wells out of the question for domestic use, but they may be attempted where larger supplies are required and no alternative is available.

Carbonate Rocks

Municipal and industrial wells with substantial yields have been drilled in various parts of the Conococheague and Beekmantown Groups in the Sinking Spring and adjacent quadrangles. Their distribution leaves no clear evidence of significant stratigraphic controls. Extrapolating studies in Lebanon County (Meisler, 1963) suggests that the Ontelaunee Formation will be the most consistently reliable source, and that the Hershey Formation is more to be compared to the Martinsburg Formation than to the other carbonates in hydrogeologic properties. The following conclusions of Meisler for Lebanon County probably remain valid here.

1. The non-shaly limestone aquifers generally yield larger supplies of water to wells than do the dolomite aquifers.
2. The maximum porosity of the carbonate rocks occurs at some distance below the water table. Reported depths to water-bearing crevices in the Lebanon Valley range from 16 to 505 feet. Seventy-five percent of the water-bearing crevices were encountered at less than 145 feet. The maximum concentration of water-bearing crevices and, hence, maximum porosity is between 70 and 80 feet below the land surfaces.
3. Groundwater in the carbonate rocks is of the calcium bicarbonate type. Nitrate contamination is common and many samples taken in this recent study contained more than 45 ppm nitrate, which is the maximum nitrate content considered acceptable by the U. S. Public Health Service. An east-west trending belt, approximately one mile north and one mile south of Pa. Route 422, shows a significant nitrate contamination. This nitrate contamination is probably the result of contamination from urban and industrial waste disposal.

The matter of contamination is a particularly serious one. Owing to the frequently cavernous nature of the rocks, various pollutants may be rapidly carried considerable distances. It is an additional problem because many people believe that sinkholes are a convenient point of discharge for storm sewage and more objectionable effluents. In view of the importance of groundwater for municipal, industrial, and commercial supplies in this area, such unlawful practices should be scrupulously avoided.

Martinsburg Formation and Hamburg Sequence

On the basis of studies of hydrology in the Martinsburg Formation in Dauphin County (Carswell and others, 1968) and Lehigh County (Poth, 1972), the following conclusions are probably valid.

1. The upland stream valleys are the most favorable topographic locations for obtaining the highest-yielding wells. Groundwater is stored and moves through these rocks in openings along joints, faults, and bedding planes.
2. As depth increases, fracture openings in the Martinsburg rocks decrease in number and size. Most wells yield water from zones that are less than 200 feet deep.
3. Well development, by adding a chemical cleaner (chiefly hexametaphosphate) and surging, proved to be an effective tool for increasing well yields. Simple well development by surging and bailing improved a well as much as 67 percent and by adding a chemical cleaner and surging, a well was improved an additional 40 percent.
4. The rocks are probably reliable for domestic supplies but yields will often not exceed 10 gallons per minute and 50 gallons per minute is the most that may be expected anywhere except possibly in the limestone of lithic type 6.

Hammer Creek Formation

The Hammer Creek Formation consists primarily of fine- to coarse-grained quartzose sandstone with interbedded quartz-pebble conglomerate, siltstone and shale. No detailed groundwater studies have been made of this formation, but generalities concerning it are obtained from the data collected by Seaber and Hollyday (1965) for the Lower Susquehanna River Basin.

1. Most wells in this formation range in yield from 55 to 480 gpm. Fifty percent of all the successful wells inventoried yielded 160 gpm or more.
2. Maximum yields may be generated from wells drilled to 400 feet deep and 10 inches in diameter.
3. The water is of good quality for most uses. It is low to moderate in dissolved solids, hardness and iron content.
4. Topographic low areas are the best sites for wells in this formation. The groundwater is nearer the land surface in stream valleys and the area of recharge is greater.

A remarkable number of springs occur in the ravine east of Vera Cruz, at the north foot of the Adamstown Ridge. The largest have been developed for the water supply of Denver. It was at first suspected that the springs might be related to faulting. However, there is no indication of disturbance or of discontinuities of the conglomerate members, which cross the ravine diagonally. It is believed that the prevalence of springs is simply a result of the relatively high relief and the great porosity of the standstones and conglomerates in the adjacent hills.

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APPENDIX A—MEASURED STRATIGRAPHIC SECTIONS

LOCALITY 1.—EAST OF ROBESONIA

Stratigraphy.—Partial section of Richland Formation.

Location.—Along the Reading Railroad from a point about 550 feet west of the crossing of a tributary to Spring Creek about 0.2 mile from the west boundary of the quadrangle to a point about 1320 feet to the east-southeast. This includes the entire width of a fairly continuous exposure where the railroad cuts a low hill.

Remarks.—Exact stratigraphic relations of this section are unknown, but it appears to be well above Locality 2.

Unit		*Thickness (Feet)* *Unit*	*Cumulative*
1	Laminated to mottled, dolomitic limestone in 4 to 5 ft. beds with occasional thin beds of unlaminated buff-weathering dolomite.	30	30
2	Beds transitional in character to units above and below.	15	45

		Thickness (Feet)	
Unit		*Unit*	*Cumulative*
3	Predominantly light-gray, laminated limestone with subordinate interbeds of buff-weathering dolomite.	38	83
4	Covered—shaly float.	4	87
5	Strongly laminated, buff-weathering dolomite.	4	89
6	Seven beds, light-gray-weathering, laminated limestone alternating with 6 beds of buff-weathering dolomite in beds averaging about 2½ ft.	29	118
7	Light-gray, recrystallized, oolitic limestone at top, increasingly mottled and irregular buff-weathering dolomite layers downward (algal structures?).	5.5	123.5
8	Light-gray limestone with strong buff-weathering laminae.	1	124.5
9	Fine-grained, silty, buff-weathering dolomite.	1.5	126
10	Medium-gray, crystalline limestone with a few quartz sand grains.	2	128
11	Buff-weathering dolomite.	2	130
12	Medium-gray, crystalline limestone.	1	131.5
13	Light-gray, magnesian limestone, weathers buff.	1.5	133
14	Buff-weathering, gray dolomite, partly silicified.	2	135
15	Medium-gray, magnesian limestone, deeply weathered, light gray, crumbly, with some buff layers containing pyrite. Top 3″ sandy and cherty.	2	137
16	Brown-weathering dolomite, strongly veined with calcite.	1.5	138.5
17	Medium-gray, oolitic limestone.	1	139.5
	Covered.	1	140.5
18	Finely crystalline, medium-gray limestone, weathers light gray; patches of small deformed oolites, dark gray, visible in light-gray, silty matrix on weathered surface.	2	142.5
19	Strongly laminated, medium-gray limestone.	1.5	144
20	Buff-weathering, medium-gray dolomite.	3.5	147.5
21	Medium- to light-gray limestone indistinctly laminated except 2″ strongly laminated at base.	2.5	150
	Covered.	1	151
22	Medium-gray limestone, weathers light gray with brown, silty laminae; small, brownish chert nodules in zones parallel to bedding.	3	154
	Covered.	2	156
23	Massive, light-gray-weathering, gray dolomite.	2	158
	Covered.	3	161
24	Buff-weathering, medium-gray dolomite with irregular (algal?) laminations.	2	163
25	Buff-weathering, gray dolomite in 2″ layers separated by silty laminae which are partly chertified.	3	166
26	2″ of very dark-gray dolomite breccia with calcite cement over irregularly laminated dolomite.	2.5	168.5
27	Buff-weathering, gray dolomite with occasional fine silty layers and brownish-black chert nodules.	3.5	172
28	Black chert, almost continuous bed.	0.5	172.5
29	Impure, buff-weathering, gray dolomite with prominent irregular silty laminae.	2.5	175

LOCALITY 2.—SINKING SPRING

Stratigraphy.—Partial section of Richland Formation.

Location.—Cut on Fritztown Road 2000 feet southwest of the main line of the Reading Railroad at Sinking Spring. Exposure in and near hinge of recumbent syncline, unit thicknesses are variable, reported values are from limbs, some units thicken in hinge.

Remarks.—This exposure is substantially lower in Richland than Locality 1. Beds 34 to 38 suggest character of Millbach Formation but lie above mappable zone of light-gray to pink limestone float.

Unit		*Thickness (Feet)*	
		Unit	*Cumulative*
1	Dolomite, medium gray, yellowish gray weathering with dark-gray chert nodules, incompletely exposed.	3.0	3.0
2	Dolomite, dark gray, finely crystalline, light olive gray with a few distinct dark shale partings.	2.3	5.3
3	Dolomitic shale, complex internal folds, yellowish gray weathering.	2.9	8.2
4	Dolomite, medium-dark gray, finely crystalline becoming medium crystalline in lower part, weathers yellowish gray with faint laminations.	3.5	11.7
5	Dolomite, medium gray, medium crystalline, weathers yellowish gray, some medium-gray chert nodules. Thickens substantially in fold nose.	3.0	14.7
6	Dolomite, dark gray, finely crystalline, distinctly shaly in lower 2″, weathers light olive gray.	1.1	15.8
7	Dolomite, dark gray, finely crystalline, weathers light olive gray with faint laminations.	0.6	16.4
8	Limestone, medium to medium gray, weathers light gray with brownish silty laminae.	2.7	19.1
9	Dolomite, 2 beds separated by 2″ shaly zone, medium- to medium-dark gray, aphanitic, weathers to light olive gray.	0.8	19.9
10	Dolomite, medium-dark gray, argillaceous and silty, weathers light grayish orange.	0.9	20.8
11	Limestone, medium gray, fine to medium crystalline, weathers light gray with yellowish gray dolomite blebs.	1.3	22.1
12	Dolomite, medium-dark gray, finely crystalline, silty, weathers light grayish brown with moderate grayish-orange laminae.	1	23.1
13	Limestone, medium crystalline, medium gray, irregularly mottled with light gray dolomite, weathers light gray with grayish yellow mottling.	2	25.1
14	Dolomite, medium-dark gray, finely crystalline, weathers grayish yellow with dark shaly laminae.	1.9	27.0
15	Sandstone, dolomitic, dark gray, weathers grayish brown, scattered lenses of buff weathering dolomite.	1.0	28.0
16	Shale, finely laminated.	0.2	28.3
17	Dolomite, medium-dark gray, medium crystalline, weathers yellowish to olive gray with some coarse brown laminae and some black chert nodules.	2.9	31.2
18	Dolomite, dark gray, very finely laminated, shaly.	0.2	31.4
19	Dolomite, medium-dark gray, medium crystalline, weathers yellowish to olive gray with some coarse brown laminae.	1.3	32.7
20	Dolomite, medium-dark gray, medium crystalline, weathers yellowish gray with some coarse brown silty laminae, 1″ of dark shale between 19 and 20.	0.8	33.5
21	Dolomite, medium gray, weathers light yellowish gray, massive.	0.9	34.4
22	Dolomite, medium-dark gray, finely crystalline, weathers light yellowish gray with few coarse brownish silty laminae.	1.9	36.3
23	Limestone, medium-dark gray, finely crystalline, weathers light gray with a few buff dolomitic laminae.	0.8	37.1

		Thickness (Feet)	
Unit		*Unit*	*Cumulative*
24	Dolomite, medium-dark gray, finely crystalline, argillaceous and silty, weathers light grayish yellow, incipient boudinage.	1.0	38.1
25	Dolomite, medium-dark gray, medium crystalline, weathers light yellowish gray, massive.	0.9	39.0
26	Dolomite, dark gray, finely crystalline, with 6″ zone of partly dolomitized medium gray, finely crystalline limestone, weathers light yellowish gray with medium-light gray limestone mottles.	2.9	41.9
27	Shale, dark gray, thickness varies considerably by flow.	1.0	42.9
28	Dolomite, medium gray, fine to medium crystalline, weathers light yellowish gray, discontinuous 3″ zone of sand lenses.	5.0	47.9
29	Dolomite, medium-dark gray, finely crystalline, weathers grayish yellow with distinct laminations.	8.0	55.9
	Fault zone—local structure complex, parts of unit 30 repeated?		
30	Limestone, dark gray, finely crystalline, coarsely laminated, grades to 10″ of yellowish weathering laminated dolomite.	3.0	58.9
31	Dolomite, medium-dark gray, finely crystalline, grades finely to coarsely laminated, weathers grayish yellow.	0.8	59.7
32	Dolomite, dark gray, argillaceous, finely laminated, weathers grayish yellow.	0.5	60.2
33	Dolomite, medium-dark gray, finely crystalline, somewhat calcareous, massive, weathers light yellowish gray.	0.7	60.9
34	Limestone, medium (pinkish) gray, finely crystalline, weathers light gray with abundant coarse buff laminae.	1.7	62.6
35	Limestone, algal, medium-light gray, light gray laminae, 3″ yellow laminated dolomite zone at base.	1.7	64.3
36	Limestone, medium gray, medium crystalline, weathers light gray with occasional contorted thin brownish laminae.	1.2	65.5
37	Limestone, sandy, medium gray, finely crystalline.	0.5	66.0
38	Shale, calcareous and silty, medium-dark gray, deeply weathered buff, poorly exposed.	1.0	67.0
39	Dolomite, limestone mottled, medium gray, fine to medium crystalline, weathers grayish yellow with light gray mottling.	0.6	67.6
40	Dolomite, medium gray, fine to medium crystalline, with sandy zone and floating sand grains, weathers light yellowish gray, incompletely exposed.	4+	71.6+

LOCALITY 3.—CACOOSING

On Open File at the Pennsylvania Geological Survey, Harrisburg, Pennsylvania.

Remarks.—This section is exactly as described by Hobson (1963) as section 12. The preserved thickness of the upper part of the Ontelaunee Formation seems about right but is more in the style of the estimates of unit thicknesses made from mapping data elsewhere in this report than a true measurement. The part of the section measured in detail has been verified and seems reliable. The beds measured here are near the hinge of a major fold and may be individually thickened somewhat. Hobson estimates an additional 420 feet of the Epler Formation extending east to a supposed fault. The structural basis for this estimate has been shown to be defective by the present mapping, and the indicated total thickness for the formation in this area is almost certainly excessive. The north limb of the fold structure in the Reading quadrangle has a crop width and apparent dip consistent with about 700 feet for the Epler interval, though the 800 feet at the type section less than 3 miles along strike may persist into this area.

LOCALITY 4.—RAILROAD CUT NEAR VINEMONT

Stratigraphy.—Partial section Hammer Creek Formation.

Location.—Top of section 2450 feet east of longitude 76°05′; 2050 feet south of latitude 40°17′30″. Location is a gully on west side of cut, as 550 feet south of crossing of Shearer Road. Base of section 2200 feet east of longitude 76°05′; 3550 feet south of latitude 40°17′30″. Location is 150 feet north of railroad culvert over small brook.

	Thickness (Feet)	
Unit	*Unit*	*Cumulative*
Fault in gully truncates the section at top.		
Medium-grained red sandstone.	3	3
Cover, probably red sandstone and some conglomerate.	18	21
Thick-bedded, coarse conglomerate, quartzite cobbles.	4	25
Red shale.	19	44
Thick-bedded, very coarse conglomerate, quartzite cobbles.	4	48
Red shale.	18	66
Massive, medium-grained, red-brown sandstone.	8	74
Red shale, with minor interbeds of red sandstone and very minor bands of conglomerate.	111	185
Thick-bedded, coarse conglomerate, quartz and quartzite pebbles.	4	189
Red shale, with a few 1-ft. to 3-ft. interbeds of red sandstone and minor conglomerates.	64	253
Cover.	22	275
Massive, coarse conglomerate with a few inches of red shale interbedded.	8	283
Interbedded red shale, medium-bedded, fine-grained red sandstone and pebbly sandstone, and minor conglomerate with quartz pebbles.	25	308
Cover.	52	360
Massive, medium-grained, reddish-brown sandstone.	12	372
Thick-bedded, coarse conglomerate with quartz pebbles and interbeds of pebbly reddish-brown sandstone.	8	380
Red sandstone and red shale, interbedded.	8	388
Cover, probably sandstone.	90	478
Red, pebbly sandstone, poorly exposed.	15	493
Medium-bedded, medium-grained, pebbly, red-brown sandstone.	4	497
Medium-bedded, fine-grained, red sandstone.	19	516
Cover.	63	579
Thick-bedded, coarse conglomerate, quartzite cobbles.	14	593
Cover.	138	731
Thick-bedded, very coarse quartzite cobble conglomerate, cobbles to 4 inches diameter.	4	735
Medium-bedded, coarse-grained, pebbly sandstone.	3	738

LOCALITY 5.—HAMMER CREEK TYPE SECTION

On Open File at the Pennsylvania Geological Survey, Harrisburg, Pennsylvania

LOCALITY 6.—REINHOLDS, PA.

On Open File at the Pennsylvania Geological Survey, Harrisburg, Pennsylvania

APPENDIX B—CHEMICAL ANALYSES AND MISCELLANEOUS TEST DATA

PRECAMBRIAN GNEISS-Radiometric Age Determinations

Potassium-argon age determinations were made on two samples from the gneiss complex of South Mountain in the Womelsdorf quadrangle for the Pennsylvania Geologic Survey by Isotopes Inc., Westwood N. J. in 1969.

Sample KA 69-110 is coarse muscovite from pegmatite in granitic gneiss at the Walters Mine, Lat. 40°17′55″W, Long. 76°10′57″W (Geyer and others, 1963).

Sample KA 69-111 is biotite separate from graphite gneiss of the third type of this report obtained as a float boulder by the road along Harnish Creek at Lat. 40°18′02″N, Long. 76°08′00″W. This sample was well foliated with unusually abundant biotite and some purple garnet, probably pyrope by X-ray diffraction.

Isotopes Inc. report the following data:

	Isotopic Age (m.y.)	sccAr ^{Rad}/gm.	Ar ^{Rad}/Ar ^{Tot}	%K
KA 69-110	804.0 ± 9	3.393×10^{-4}	0.70	8.51
KA 69-111	741.5 ± 7	2.547×10^{-4}	0.98	7.05

Constants used for calculation are: $\lambda\beta = 4.72 \times 10^{-10} y^{-1}$, $\lambda_e = 0.585 \times 10^{-10} y^{-1}$, and $K^{40} = 1.19 \times 10^{-4}$ at K.

The indicated error for reported ages considers all sources of analytic error only. Error computed by RMS summation of errors method.

Other radiometric ages in Pennsylvania for comparison may be found in Lapham, D. M. and Root, S. I., 1971, Summary of Isotopic Age Determinations in Pennsylvania, Pa. Geol. Survey, 4th ser., Information Circular 70.

HARDYSTON FORMATION

No analytic data have been reported from the Sinking Spring quadrangle, though refractory material has been quarried. The two samples of refractory material reported below come from South Mountain in the Womelsdorf quadrangle and from the hill immediately east of the Sinking Spring quadrangle in the Reading quadrangle (Moore & Taylor, 1924, p. 34). The analyses are quite similar and presumably representative of the intervening rock.

Analyses and tests on samples of Hardyston quartzite

Sample no.	SiO_2	Al_2O_3	Fe_2O_3	CaO	Total per-cent	Fusion point degrees C.	
						Coarser material	Through 150 mesh
56	97.92	0.80	0.85	0.09	99.66	1,772	1,760
64	97.20	1.08	1.35	n.d.	99.63	1,734	1,735

RICHLAND FORMATION

Data reported by Gray (1951, p. 59) for a quarry 2 miles east of Wernersville, south of US 422, Location 1 on Geologic Map.

Lithology: Interbedded, massive dolomite and blue, laminated limestone. One bed of limestone is light gray to white, soft, crystalline, with indistinct laminations. Black chert is present in the dolomite and the blue limestone.

Sample location and sequence: Samples were taken across the floor and part way up the South face near the center of the quarry which is elongate parallel to the strike. Analyses are arranged in stratigraphic order.

Face Height: 40 feet at highest point.

Analyses of Samples:

No.	Fe_2O_3	Al_2O_3	SiO_2	$CaCO_3$	$MgCO_3$	Length	Remarks
171	0.52	0.76	2.83	93.80	1.86	6′	Limestone in S face.
170	0.85	0.88	5.77	71.35	20.73	6′	Dl. and some light-gray ls.
169	0.56		7.74	90.07	1.07	4′	Light-gray, crystalline ls.
168	0.80	1.43	8.08	69.50	20.10	15′	Dolomitic ls., chert & sand grains.
167	0.40		4.08	92.37	2.42	20′	Ls. with dl. boudins.
166	1.57	1.17	5.55	54.20	37.40	1′	Dl. with gash veins.

EPLER FORMATION

The following partial analysis is reported by E. J. Brenneman, Inc. for run of the quarry at their quarry near Cacoosing, Location 2 on the Geologic Map (O'Neill, 1964): $CaCO_3$ 75.6%, $MgCO_3$ 5.6%, SiO_2 12.3%, P.O. .2%, specific gravity 2.69, absorption 0.62%, Data reported by Gray (1951, Locality 11, p. 36) for a quarry north of Rickenbach in the Temple quadrangle gives some representative bed analyses.

Lithology: Dolomite, alternating with limestone or magnesian limestone. The dolomite is gray, massive with occasional faint lamination. The limestone is blue with faint lamination and fucoidal mottling.

Sample location and sequence: Samples taken in the inner, lower level of the quarry. No. 187 is from the oldest of the beds sampled.

Analyses of Samples:

No.	Fe_2O_3	Al_2O_3	SiO_2	$CaCO_3$	$MgCO_3$	Length	Remarks
193	0.38	1.42	2.80	72.67	22.73	15′	Dl. with thin ls. interbeds.
192	0.86		4.06	76.01	18.68	8′	Dolomite.
191	0.52		2.82	89.84	6.39	2′6″	Faintly laminated ls.
190	2.12		6.20	58.88	33.24	3′6″	Massive dl. and laminated ls.
189	0.48		1.42	93.75	4.24	6′	Gray ls., in part mottled.
188	1.68		3.68	60.13	35.04	10′6″	Dl., in part banded.
187	1.18		3.06	60.85	34.88	10′	Massive, gray dl. includes thin beds of ls.

ONTELAUNEE FORMATION

Analytic data is not available from the Sinking Spring quadrangle but the following two localities reported by Gray (1951, p. 60) are within a few miles of the quadrangle in the Temple quadrangle and are believed to be representative.

Location: 2.15 mi. S. of West Leesport, Bern Township.

Quadrangle: Temple *Lat.* 0.64 mi. S. of 40°25′N
Long. 1.31 mi. E. of 76°00′W

Lithology: Laminated blue limestone. Laminations stand out as brown, silty ridges on weathered surface. Limestone is interbedded with massive gray dolomite.

Sample location and sequence: Samples are located at extreme North end of the quarry. Complex folding and/or faulting makes age relations difficult to determine. No. 332 lies west of No. 331.

Analyses of Samples:

No.	Fe_2O_3	Al_2O_3	SiO_2	$CaCO_3$	$MgCO_3$	Length
331	0.60	1.02	3.28	90.34	4.76	13′
332	0.40	0.74	1.24	72.67	24.95	7′6″

Location: 3 mi. S. of West Leesport, Bern Township.

Quadrangle: Temple *Lat.* 1.04 mi. S. of 40°25′N
Long. 1.54 mi. E. of 76°00′W

Lithology: Gray, thick-bedded dolomite and blue limestone alternating with dolomite in 1—2 inch bands.

Sample location and sequence: Samples taken from outcrops on the South bank of the Schuylkill River, at the water's edge. No. 335 directly overlies No. 334.

No.	Fe_2O_3	Al_2O_3	SiO_2	$CaCO_3$	$MgCO_3$	Length	Remarks
335	0.40	0.66	1.34	79.74	17.86	7′	Banded ls. and dl.
334	0.60	0.58	1.90	65.80	31.12	7′	Gray dl., fetid when struck with hammer.

MYERSTOWN FORMATION

The following analyses have been reported by Gary (1951, p. 69 & 70).

Location: 1.5 mi. W. of Wernersville, Location 3 of Geologic Map.

Lithology: Dark-blue, finely crystalline, thin-bedded limestone. Weathers light-bluish-gray with light and dark striations on the bedding surfaces. A few scattered fragments of crinoid stems.

Sample location and sequence: Samples are from two outcrops on the North side of the highway. No. 305 is probably the older.

Analyses of Samples:

No.	Fe_2O_3	Al_2O_3	SiO_2	$CaCO_3$	$MgCO_3$	Length
306	1.00	1.50	7.24	80.33	9.93	3′
305	0.60	0.40	5.76	86.42	6.82	3′

Location: 1.5 mi. W. of Wernersville, Location 4 of Geologic Map.

Lithology: Dark-blue, dense, thin-bedded limestone with crinoid fragments.

Sample location and sequence: Sample is from a dip slope exposure of only a few thin beds.

No.	Fe_2O_3	Al_2O_3	SiO_2	$CaCO_3$	$MgCO_3$	Length
307	0.72	0.40	4.28	87.40	7.20	2′

Location: 1.5 mi. W. of Wernersville, Location 5 of Geologic Map.

Lithology: Dense, blue-gray, thin-bedded limestone with calcarenite layers. Crinoid fragments associated especially with the calcarenite. Two layers of sericitic shale, separated by 4″ of limestone, are interpreted as metabentonite.

Sample location and sequence: Sample No. 308 is from North side of highway and relation to others is uncertain. No. 310 overlies No. 309 on the South side of the highway.

No.	Fe_2O_3	Al_2O_3	SiO_2	$CaCO_3$	$MgCO_3$	Length	Remarks
308	0.80	0.66	3.94	87.40	7.20	5′4″	
310	1.20	3.24	8.64	81.51	5.41	2′±	Metabentonite not included.
309	1.00	3.40	10.36	75.81	9.43	3′6″	

Location: 2 mi. NW of Wernersville, Location 6 of Geologic Map.

Sample location and sequence: Samples from east end of small, partially filled quarry. No. 313 overlies No. 314.

No.	Fe_2O_3	Al_2O_3	SiO_2	$CaCO_3$	$MgCO_3$	Length
314	0.80	0.94	8.00	84.06	6.20	6′6″
313	1.10	1.66	9.16	80.03	8.05	6′±

HERSHEY FORMATION

Two representative localities from the Sinking Spring quadrangle are reported by Gray (1951, p. 80).

Location: 1 mi. North of Womelsdorf, Location 7 of Geologic Map.

Lithology: Dark-gray, finely crystalline, thin-bedded limestone.

Sample location and sequence: Samples cut in beds exposed in floor of abandoned road. No. 319 is fartherest North outcrop. As beds are believed to be overturned, it is younger than 320, which was cut from beds exposed a few yards to South.

Analyses of Samples:

No.	Fe_2O_3	Al_2O_3	SiO_3	$CaCO_3$	$MgCO_3$	Length	Remarks
319	2.80	5.14	20.76	60.88	10.42	14′	Only 8′ exposed but sample spans 14′.
320	2.10	5.04	15.00	71.69	6.17	17′	

Location: E. end of Wernersville Borough, Location 8 of Geologic Map.

Lithology: Thin-bedded, gray shaly limestone. A few beds weathered to porous shale and not included in the samples.

Sample location and sequence: Samples are from exposures on East side of street. Sample No. 327 overlies No. 326.

No.	Fe_2O_3	Al_2O_3	SiO_2	$CaCO_3$	$MgCO_3$	Length	Remarks
327	1.40	4.86	14.46	73.85	5.43	13′	Only 8′ of the 13′ exposed.
326	1.40	4.48	18.56	68.94	6.62	20′	Only 12′ of the total are exposed.

A residual clay apparently derived from the Jacksonburg Formation was sampled in preparation of this report. Analysis and physical tests are part of a continuing program of clay and shale evaluation in Pennsylvania.

Sample No.: 177-5-5

Location: Sample collected from stream bank immediately west of a secondary road 3.69 miles north-northwest of Wernersville (Location 9 of Geologic Map).

Description: Unknown thickness (greater than one foot) of residual clay is exposed in stream bank, with about 3.5 feet of soil overburden. Similar clay in plowed fields nearby to southeast (mixed with soil by cultivation) suggests the deposit may be fairly extensive.

Attitude of bedding: Residual deposit presumably about parallel to land surface.

Sampled interval: Grab sample.

Type of material: Residual clay.

Slow-Firing Tests:

Temp. °F	Color	Hardness	% Shk.	% Absorb.	Approx. Sp. Gr.[1]
1800	Tan	moh's 3	5.0	18.0	1.77
1900	"	" 4	5.0	14.2	1.88
2000	"	" 4	7.5	11.6	1.97
2100	Lt. brown	" 5	10.0	3.5	2.22
2200	Gray brown	" 6	12.5	0.5	2.30
2300			Expanded		
2400					

[1] Bulk Density gm/cc

Bloating test: Negative

Other Tests: Does not effervesce with HCl.

Semi-quantitative spectographic analysis showed the following abundance of trace elements: Ba (20.1%), Sr, Zr, and V ($> .001 < 0.1\%$). Other elements such as Zn, Cu, Cr, and Ni, if present, are less than 0.001%.

Potential Uses: Should fire to "MW" face brick specifications at about 2000°F, structural tile.

Chemical Analysis:

	%
SiO_2	66.50
Al_2O_3	17.52
Fe_2O_3	3.44
FeO	0.65
CaO	0.17
MgO	1.39
CO_2	0.02
Na_2O	0.68
K_2O	2.99
TiO_2	0.99
P_2O_5	0.07
MnO	0.04
L.O.I. @ 1,000°C	4.98
H_2O @ 110°C	1.18
Comb. H_2O	4.86
S (total)	0.00
C (total)	0.18

[3] Nitrogen atmosphere

Mineralogy: (X-ray):

	%	Accuracy (±)
Quartz	41	5
Mica	39	6
Kaolinite	0	—
C-V-Mo	13	3
Feldspar	2	1

Other Tests:

pH: 5.3
Water of plasticity %: 22.8
% Drying shrinkage: 2.5
Drying characteristic: no drying defects
Dry strength: Fair
Workability: Low plasticity
U.S.B.M. Laborary (Preliminary Tests) Tuscaloosa

MARTINSBURG FORMATION

Lithic Type 1: Gray (1951, p. 84, locality 80) provides the following analyses from a small abandoned quarry near the intersection of Wooltown Road and Ruth Avenue.

Location: 1 mi. North of Wernersville.

Lithology: Dark-gray, limy shale; brown on weathered surface. Cleavage is well-developed. Fresh surfaces have a velvety luster.

Sample location and sequence: Sample No. 324 overlies No. 323 in the quarry. No. 325 is from the road south of the quarry and is younger than No. 324.

Analyses of Samples:

No.	Fe_2O_3	Al_2O_3	SiO_2	$CaCO_3$	$MgCO_3$	Length	Remarks
325	5.60	11.72	15.50	32.41	34.77	5′6″	These beds are believed to be in the transition zone at the base of the Martinsburg formation.
324	5.20	12.96	40.84	23.57	17.42	7′	
323	5.80	14.20	42.84	21.60	15.56	9′	

Lithic Type 2: The following data from O'Neill and others (1965, p. 85-86) from the Temple quadrangle is probably representative of the composition and use of Lithic type 2 shales in the Sinking Spring quadrangle.

Sample No.: 187-1-2

Quadrangle: Reading 15′; Temple 7½′.

Location: Glen-Gery Shale Brick Corporation quarry north-northeast of its Shoemakersville plant.

Geologic Unit: Martinsburg Formation, Ordovician age.

Description: The rock consists of yellow-gray shale beds which in general range from 2 to 6 inches in thickness. Interbedded with these shales are a few siltier beds. The shales weather to various shades of yellow and brown. The quarry workings are extensive, measuring more than 500 feet by 1000 feet in plan and averaging over 20 feet in height.

Attitude of Bedding: None taken.

Sampled Interval: Grab sample from broken rock at the working face.

Type of Material: Clay.

Chemical Analysis:

	%
SiO_2	60.90
Al_2O_3	17.50
Fe_2O_3	5.66
FeO	2.44
CaO	.14
MgO	1.46
K_2O	3.60
Na_2O	.90
TiO_2	1.01
L.O.I.	6.33
S	.01
CO_2	.66
comb. H_2O	4.95
H_2O @ 120°C	.72

Mineralogy: (X-ray):

	%	Accuracy (±)
Quartz	43	8
Mica	33	10
Kaolinite	1	3
C-V-Mo	11	8
Feldspar	3	3

Other Tests:

pH: 7.40
Workability: fairly plastic, short and fine grit
Water of plasticity %: 23.0
% Drying shrinkage: 3.0
Dry strength: low

Slow-Firing Tests:

Temp. °F.	Color	Hardness	% Shk.	% Absorb.	Approx. Sp. Gr.
1800	Dk. buff brown	Soft, crumbly	3.0	21.1	2.68
1900	Dk. buff brown	Soft, crumbly	4.0	18.8	2.69
2000	Lt. brown	Hard	7.5	13.1	2.62
2100	Dk. brown	Very hard	11.0	6.4	2.55
2200	Gray black	Steel hard	12.5	2.4	2.44
2300	Melted and expanded				

Bloating Test: Positive.

Bloating Tests (Quick-Firing):

Crushing characteristics: Good
Drying characteristics: Good
Particle size: −½ + ¼″
Retention time: 15 Min.

Temp. °F	Bulk Density	Lb/Ft³	% Absorb.	Remarks
1900	2.18	135.8	7.4	No bloating
2000	2.30	143.2	3.7	No bloating
2100	2.19	136.4	2.8	No bloating
2200	1.32	82.2	2.1	Good expansion

Evaluation: Fair lightweight aggregate.

Potential Uses: Brick and fair lightweight aggregate.

Lithic Type 5: O'Neill and others (1965, P. 77-78) provide the following data from the Bernville quadrangle for vari-colored shales within two miles of the lithic type 5 outcrop of the Sinking Spring quadrangle. The exposure is not continuous but the rocks appear to be identical.

Sample No.: 177-6-2

Quadrangle: Wernersville 15′; Bernville 7½′.

Location: Outcrop on the south side of Pa. Route 183 immediately south of Mt. Pleasant.

Geologic Unit: Matrinsburg Formation, Ordovician Age.

Description: Thin-bedded, vari-colored shales of the Martinsburg Formation are exposed a distance of 900 feet along the roadcut. The predominant colors of the shales are light olive gray and green gray but some beds are purple, red or tan. The exposure is over 20 feet high and has soil overburden which is generally less than one foot thick at the surface.

Attitude of Cleavage: N70E, 80SE; (bedding is not discernible).

Sample Interval: Composite taken every 25 feet along the 900-foot extent of the exposure.
Type of Material: shale.

Chemical Analysis:

	%
SiO_2	58.70
Al_2O_3	19.70
Fe_2O_3	6.64
FeO	2.76
CaO	.11
MgO	1.22
K_2O	3.57
Na_2O	1.15
TiO_2	.95
L.O.I.	5.12
S	.006
CO_2	.66
Comb. H_2O	4.46

Mineralogy: (X-ray):

	%	Accuracy (±)
Quartz	27	6
Mica	50	10
Kaolinite	9	7
C-V-Mo	5	3
Feldspar	1	3

Remarks: quartz may be too high

Other Tests:

pH: 7.1
Workability: not plastic, short
Water of plasticity %: 16.0
% Drying shrinkage: 2.5
Dry strength: very low

Slow-Firing Tests:

Temp. °F.	Color	Hardness	% Shk.	% Absorb.	Approx. Sp. Gr.
1800	Dk. buff brown	Soft, crumbly	2.5	15.8	2.77
1900	Dk. buff brown	Soft, crumbly	3.5	13.2	2.73
2000	Dk. brown	Hard	5.0	10.0	2.70
2100	Dk. brown	Very hard	6.0	8.6	2.69
2200	Very dk. brown	Steel hard	7.0	6.0	2.62
2300	Expanded and melted		Exp.		

Bloating Test: Slight.

Potential Uses: Possibly brick, floor tile and sintered aggregate.

IRON ORES OF WHEATFIELD AREA

The following analyses obtained by d'Invilliers (1883) are from the main workings of the Wheatfield Mine at the east end of the limestone inlier except No. 5, which is from the Ruth Mine at the western end.

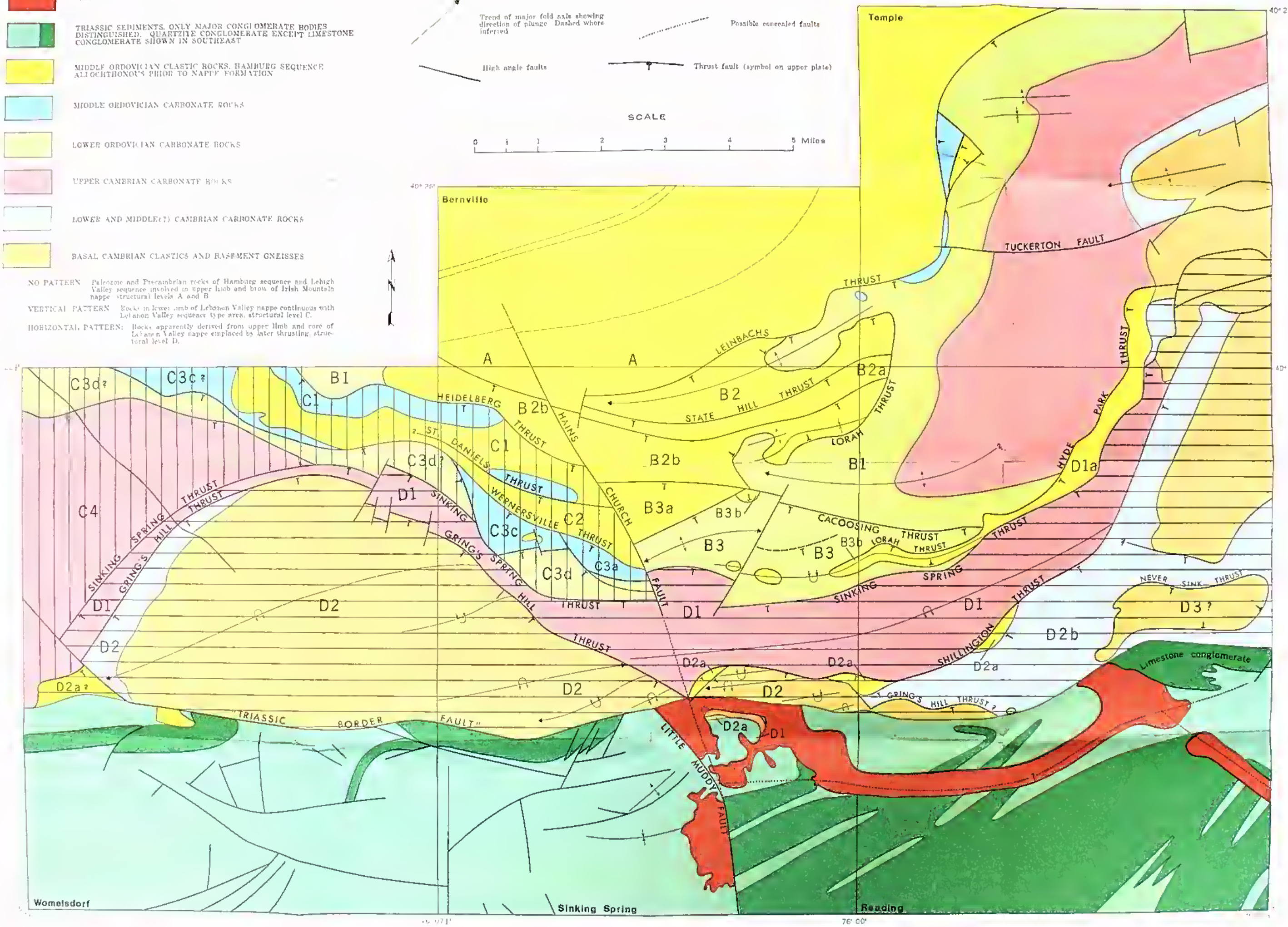
	1	2	3	4	5
Metallic iron	37.00	41.025	37.80	39.60	42.573
Metallic Manganese		.137		.23	
Metallic Copper		.005		.12	
S	.85	1.203	.91		
P	.03	.020	.02		
Fe_2O_3	50.07			15.42	
FeO				37.05	
MnO	0.31			.30	
Al_2O_3	2.35	1.398	3.60	5.90	3.270
CaO	2.60	2.750	3.57	1.90	2.080
MgO	13.10	13.848	13.34	11.38	
SiO_2	20.01	17.960	19.60	20.20	21.850
FeS_2 (Pyrite)	1.59			3.58	
$CuFeS_2$ (Chalcopyrite)				.15	
CO_2	9.30			2.50	
H_2O	.60			1.25	

Minerals reported at this locality: magnetite, pyrite, chalcopyrite, serpentine, calcite, flourite, prochlorite, stilbite, amythystine quartz, native copper.

2674

TOPOGRAPHIC AND GEOLOGIC SURVEY
Arthur A. Socolow, *State Geologist*

COMMONWEALTH OF PENNSYLVANIA
DEPARTMENT OF ENVIRONMENTAL RESOURCES



EXPLANATION

🟥 TRIASSIC MORGANTOWN DIABASE SHEET

🟩 TRIASSIC SEDIMENTS. ONLY MAJOR CONGLOMERATE BODIES DISTINGUISHED. QUARTZITE CONGLOMERATE EXCEPT LIMESTONE CONGLOMERATE SHOWN IN SOUTHEAST

🟨 MIDDLE ORDOVICIAN CLASTIC ROCKS. HAMBURG SEQUENCE ALLOCHTHONOUS PRIOR TO NAPPE FORMATION

🟦 MIDDLE ORDOVICIAN CARBONATE ROCKS

🟨 LOWER ORDOVICIAN CARBONATE ROCKS

🟪 UPPER CAMBRIAN CARBONATE ROCKS

⬜ LOWER AND MIDDLE(?) CAMBRIAN CARBONATE ROCKS

🟧 BASAL CAMBRIAN CLASTICS AND BASEMENT GNEISSES

NO PATTERN Paleozoic and Precambrian rocks of Hamburg sequence and Lehigh Valley sequence involved in upper limb and brow of Irish Mountain nappe structural levels A and B

VERTICAL PATTERN Rocks in lower limb of Lebanon Valley nappe continuous with Lebanon Valley sequence type area, structural level C.

HORIZONTAL PATTERN: Rocks apparently derived from upper limb and core of Lebanon Valley nappe emplaced by later thrusting, structural level D.

SYMBOLS

Trend of major fold axis showing direction of plunge Dashed where inferred

Possible concealed faults

High angle faults

Thrust fault (symbol on upper plate)

SCALE

0 ½ 1 2 3 4 5 Miles

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Commonwealth of Pennsylvania
Virginia Milewski, Cartographer

TECTONIC MAP SHOWING STRUCTURAL LEVELS OF SINKING SPRING AND ADJACENT QUADRANGLES

D. B. MacLachlan
T. V. Buckwalter
D. B. McLaughlin

SYNOPTIC FABRIC DIAGRAMS FOR THREE DEFORMATIONAL PHASES

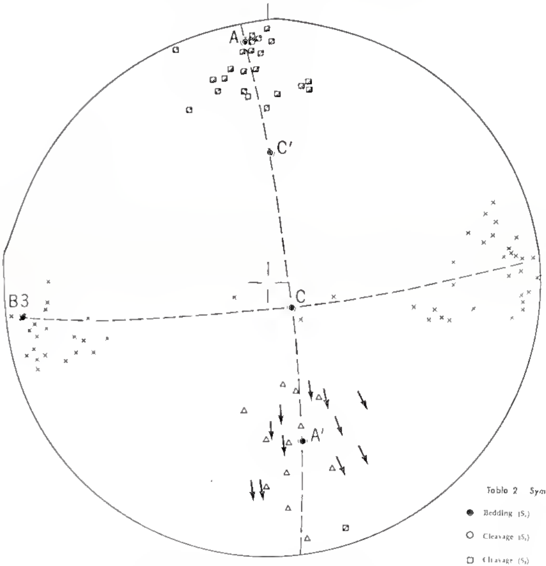

Figure 51 Synoptic diagram of D_1 fabric elements in Sinking Spring quadrangle. S_1 in shale distinguished by half solid symbols. Lettered points are deduced kinematic axes of the deformation. Arrows represent minor fault slicks with southerly plunge taken from Figure 42 for comparison with La_1. Other symbols as in Table 2. The girdle BC is visual best fit for the trace of mean S_1 as defined by L_{01} and other intersection lineations. A is the BC girdle pole and the AC circle is fitted through A and the mean of La_1.

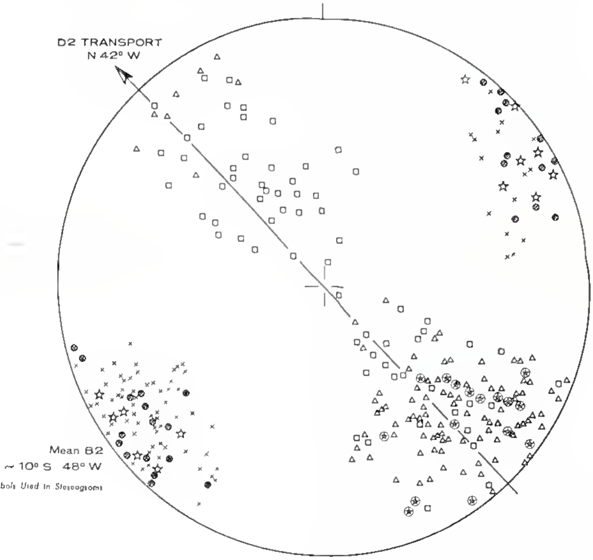

Figure 52 Synoptic diagram of D_2 fabric elements in the Sinking Spring quadrangle. Symbols in diagram identified on Table 2. Some folds, normal to La_2, are original D_2 structures but L_{120} lineations and some folds appear to be reoriented D_1 structures. Cross folds parallel to La_2 can be more readily distinguished from D_1 structures by their orientation. Complete girdle defined by S_2 poles is obviously related to D_2 movement but mechanical explanation is uncertain. Intersection lineations recorded are predominantly L_{210} from carbonates and L_{211} from argillaceous rocks.

Table 2 Symbols Used in Stereograms

●	Bedding (S_0)	
○	Cleavage (S_1)	
□	Cleavage (S_2)	
⊠	Cleavage (S_1), also on figure 51 ▣	
★	Fold axis (B)	open symbol younger, where 2
☆	Fold axis (B)	
⊗	L_{01} or other L_0 lineations	
×	Intersection lineation—usually L_{01}, L_{02}, L_{12}, L_{01}	
▲	La lineation	open symbol younger(?) where 2
△	La lineation	
✪	Crossfold axis (B_c)	
╤	Statistical fold axis derived from girdle of planar elements	

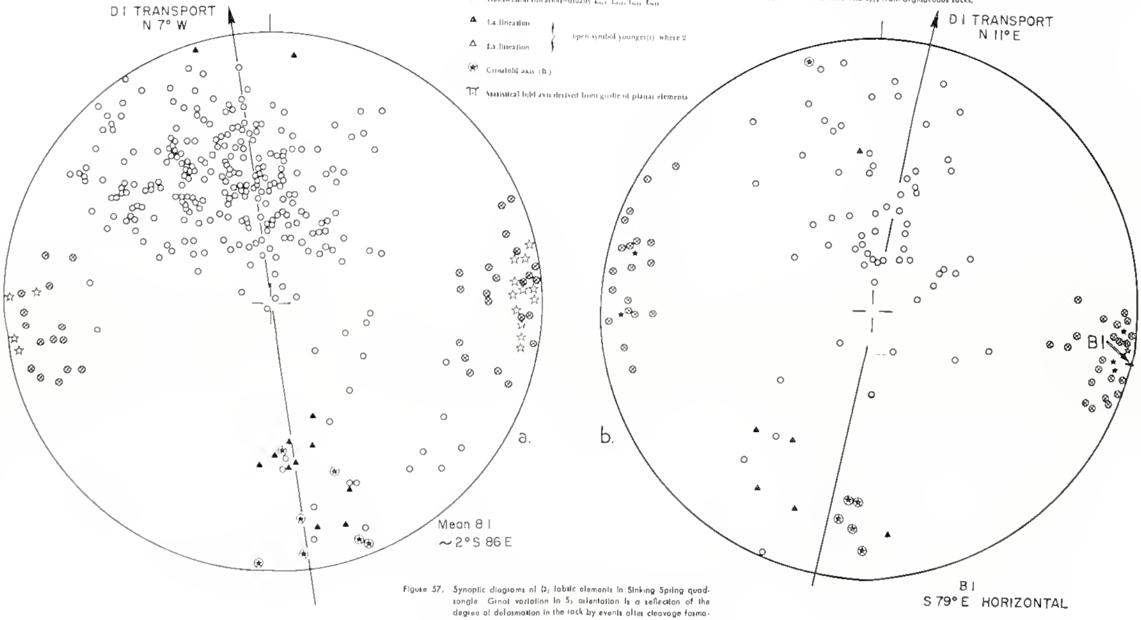

Figure 57. Synoptic diagrams of D_1 fabric elements in Sinking Spring quadrangle. Great variation in S_1 orientation is a reflection of the degree of deformation in the rock by events after cleavage formation. The S_1 girdle defines a regional fold axis B_1^1 in cleavage, consistent with B_1 (Figure 52). La_1 is sensitive to destruction by inclined movements and surviving examples approximate their original orientation. Folds identified as B_1 are residue not falling geometrically in the influence of B_2.

a) Fabric of Irish Mountain nappe and associated rocks

b) D_1 fabric of Lebanon Valley nappe rocks.

TOPOGRAPHIC AND GEOLOGIC SURVEY
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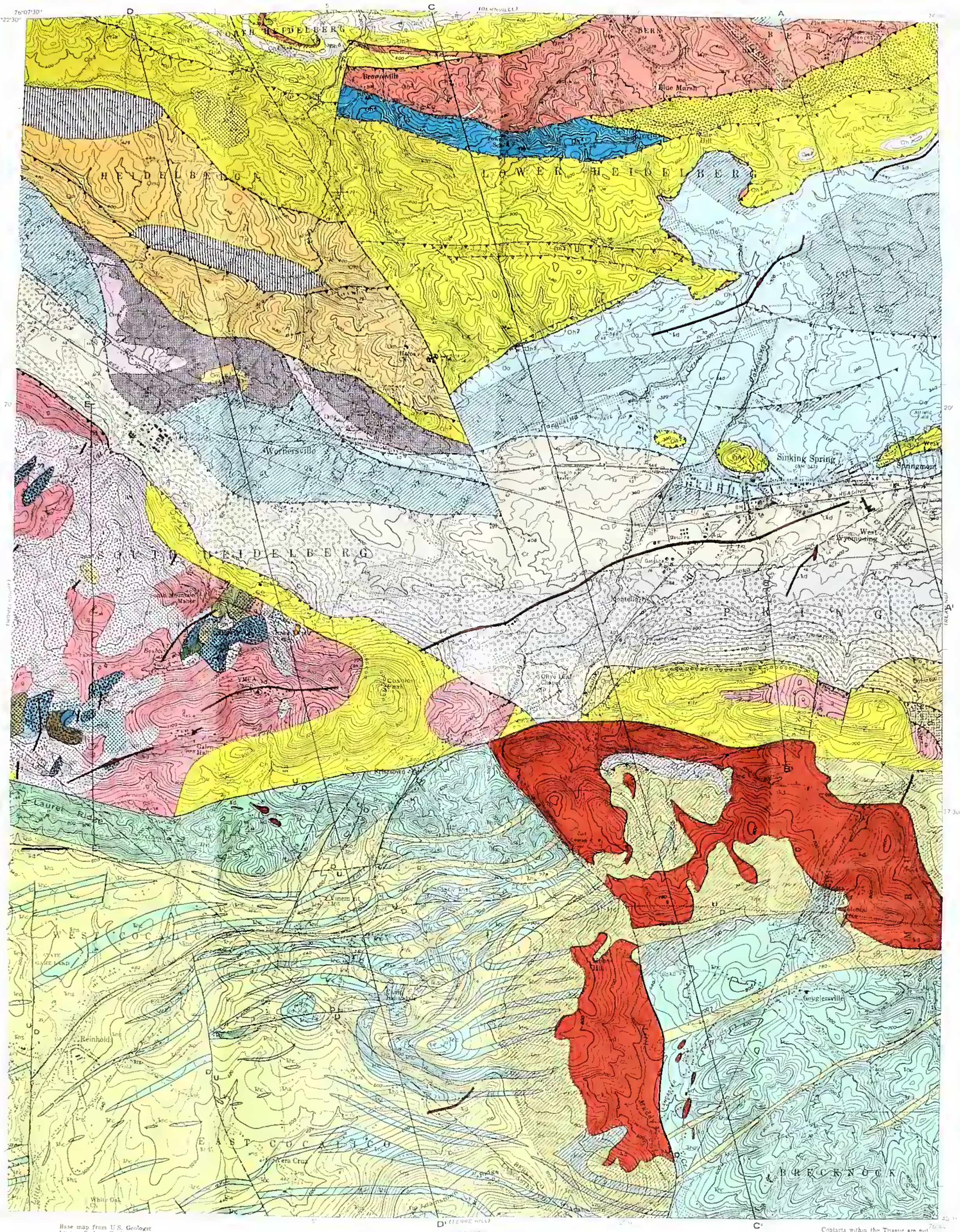


Base map from U.S. Geologic Survey Sinking Spring 7½-minute quadrangle

Copyright 1975 by the Commonwealth of Pennsylvania

Virginia Milewski, Cartographer

SCALE 1:24 000

CONTOUR INTERVAL 20 FEET
DATUM IS MEAN SEA LEVEL

UTM GRID AND 1968 MAGNETIC NORTH DECLINATION AT CENTER OF SHEET

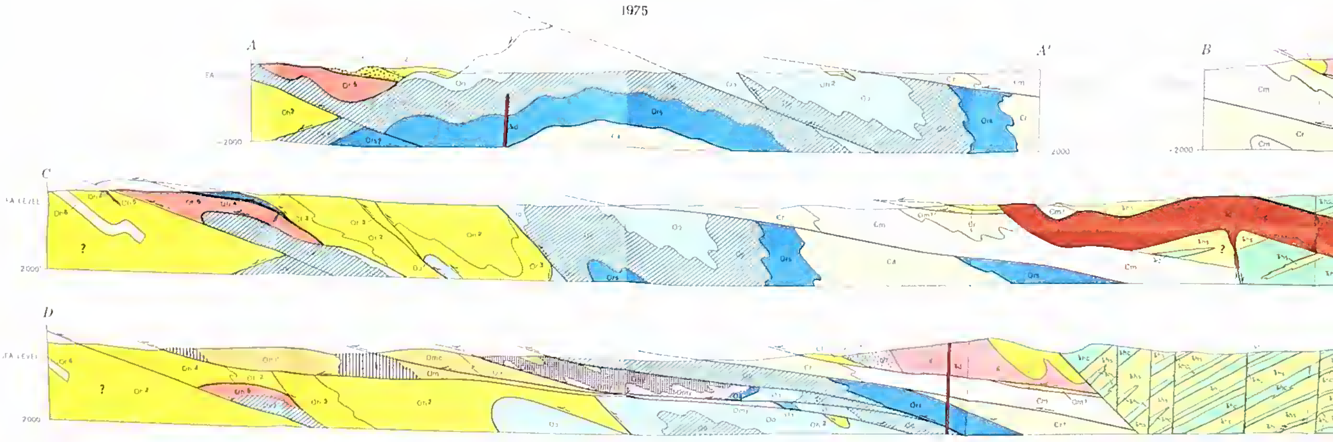
Contacts within the Triassic are not distinguished with respect to quality; data was lost in 1972 Flood

GEOLOGIC MAP OF THE SINKING SPRING 7½-MINUTE QUADRANGLE, PENNSYLVANIA

By

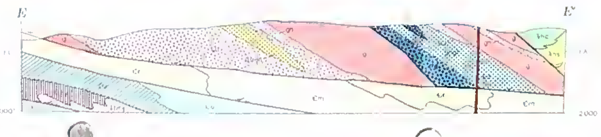
DAVID B. MacLACHLAN, TRACY V. BUCKWALTER and DEAN B. McLAUGHLIN

1975



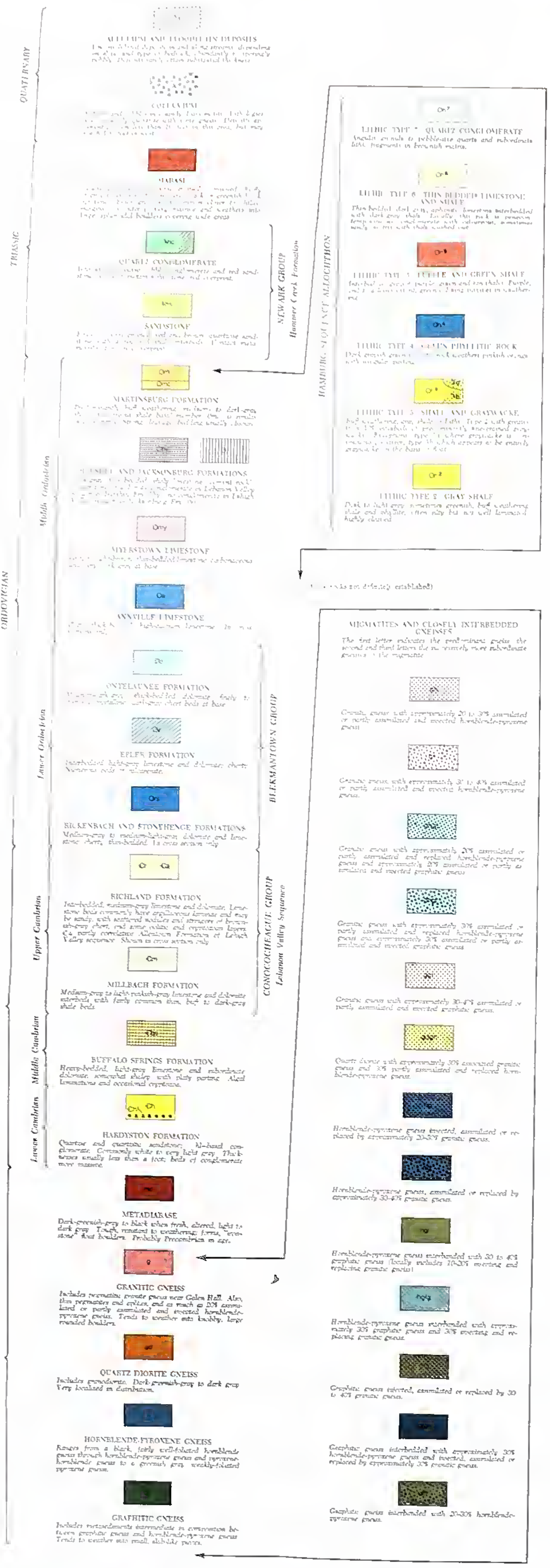
CROSS SECTIONS

(Same scale as map scale; no vertical exaggeration)



COMMONWEALTH OF PENNSYLVANIA
DEPARTMENT OF ENVIRONMENTAL RESOURCES

EXPLANATION



ALLUVIUM AND FLOODPLAIN DEPOSITS
[illegible]

COLLUVIUM
[illegible]

DIABASE
[illegible]

QUARTZ CONGLOMERATE
[illegible] conglomerate and red sandstone [illegible]

SANDSTONE
[illegible]

MARTINSBURG FORMATION
[illegible]

HERSHEY AND JACKSONBURG FORMATIONS
[illegible] Lebanon Valley [illegible] Lehigh [illegible]

MYERSTOWN LIMESTONE
[illegible]

ANNVILLE LIMESTONE
[illegible]

ONTELAUNEE FORMATION
[illegible] thick-bedded dolomite [illegible] chert beds at base.

EPLER FORMATION
Interbedded light-gray limestone and dolomite; cherty. Numerous [illegible]

RICKENBACH AND STONEHENGE FORMATIONS
Medium-gray to medium-light-gray dolomite and limestone; cherty, thin-bedded. In cross section only.

RICHLAND FORMATION
Interbedded, medium-gray limestone and dolomite. Limestone beds commonly have argillaceous laminae and may be sandy, with scattered nodules and stringers of brownish-gray chert, and some oolitic and cryptozoon layers. [illegible] Allentown Formation of Lehigh Valley sequence. Shown in cross section only.

MILLBACH FORMATION
Medium-gray to light-reddish-gray limestone and dolomite interbeds, with fairly common thin, buff to dark-gray shale beds.

BUFFALO SPRINGS FORMATION
Heavy-bedded, light-gray limestone and subordinate dolomite, somewhat shaley, with platy parting. Algal limestones and occasional cryptozoa.

HARDYSTON FORMATION
Quartzite and quartzitic sandstone; [illegible] conglomerate. Commonly white to very light gray. Thicknesses usually less than a foot; beds of conglomerate more massive.

METADIABASE
Dark-greenish-gray to black when fresh, altered, light to dark gray. Tough, resistant to weathering; forms "ironstone" float boulders. Probably Precambrian in age.

GRANITIC GNEISS
Includes pegmatitic granite gneiss near Galen Hall. Also, thin pegmatites and aplites, and as much as 20% assimilated or partly assimilated and injected hornblende-pyroxene gneiss. Tends to weather into knobby, large rounded boulders.

QUARTZ DIORITE GNEISS
Includes granodiorite. Dark-greenish-gray to dark gray. Very localized in distribution.

HORNBLENDE-PYROXENE GNEISS
Ranges from a black, fairly well-foliated hornblende gneiss through hornblende-pyroxene gneiss and pyroxene-hornblende gneiss to a greenish gray, weakly-foliated pyroxene gneiss.

GRAPHITIC GNEISS
Includes metasediments intermediate in composition between graphitic gneiss and hornblende-pyroxene gneiss. Tends to weather into small, slabby pieces.

LITHIC TYPE 7 QUARTZ CONGLOMERATE
Angular granule to pebble-size quartz and subordinate [illegible] fragments in brownish matrix.

LITHIC TYPE 6 THIN BEDDED LIMESTONE AND SHALE
Thin-bedded, dark gray, aphanitic limestone interbedded with dark gray shale. Locally, this rock is [illegible] conglomerate with [illegible] shale [illegible]

LITHIC TYPE 5 PURPLE AND GREEN SHALE
Interbedded [illegible] purple, green and tan shales. Purple, [illegible] in southern [illegible]

LITHIC TYPE 4 GREEN PHYLLITIC ROCK
Dark greenish gray [illegible] weathers pinkish orange with [illegible]

LITHIC TYPE 3 SHALE AND GRAYWACKE
Buff weathering, gray shale [illegible] Type 2 [illegible] graywacke [illegible]

LITHIC TYPE 2 GRAY SHALE
Dark to light gray, sometimes greenish, buff weathering shale and argillite, often silty but not well laminated; highly cleaved.

[illegible] is not definitely established)

MIGMATITES AND CLOSELY INTERBEDDED GNEISSES
The first letter indicates the predominant gneiss, the second and third letters the successively more subordinate gneisses of the migmatite.

Granitic gneiss with approximately 20 to 30% assimilated or partly assimilated and injected hornblende-pyroxene gneiss.

Granitic gneiss with approximately 30 to 40% assimilated or partly assimilated and injected hornblende-pyroxene gneiss.

Granitic gneiss with approximately 20% assimilated or partly assimilated and replaced hornblende-pyroxene gneiss and approximately 20% assimilated or partly assimilated and injected graphitic gneiss.

Granitic gneiss with approximately 30% assimilated or partly assimilated and replaced hornblende-pyroxene gneiss and approximately 30% assimilated or partly assimilated and injected graphitic gneiss.

Granitic gneiss with approximately 30-40% assimilated or partly assimilated and injected graphitic gneiss.

Quartz diorite with approximately 30% associated granitic gneiss and 30% partly assimilated and replaced hornblende-pyroxene gneiss.

Hornblende-pyroxene gneiss injected, assimilated or replaced by approximately 20-30% granitic gneiss.

Hornblende-pyroxene gneiss, assimilated or replaced by approximately 30-40% granitic gneiss.

Hornblende-pyroxene gneiss interbedded with 30 to 40% graphitic gneiss (locally includes 10-20% injecting and replacing granitic gneiss).

Hornblende-pyroxene gneiss interbedded with approximately 30% graphitic gneiss and 30% injecting and replacing granitic gneiss.

Graphitic gneiss injected, assimilated or replaced by 30 to 40% granitic gneiss.

Graphitic gneiss interbedded with approximately 30% hornblende-pyroxene gneiss and injected, assimilated or replaced by approximately 30% granitic gneiss.

Graphitic gneiss interbedded with 20-30% hornblende-pyroxene gneiss.

ENVIRONMENTAL GEOLOGIC FACTORS

ENGINEERING PROPERTIES

Much of this information on the rocks of this quadrangle is basic data needed for land use planning and in designing most engineering construction jobs. Any man made structure should be adapted to the topographic and geologic environment shown and discussed in this report.

GROUND WATER AVAILABILITY

Information on the water-bearing properties of the rocks in this area will help in evaluating the quantity and quality of ground water available and will aid in choosing locations, depths and conditions most favorable for the desired ground water yield. Detailed ground water and water well data are available as open file at the U.S. Geological Survey offices in Harrisburg, for anyone who desires the latest information.

ENGINEERING PROPERTIES	FORMATION	GROUND WATER AVAILABILITY
Poor foundation material; easily excavated, thickness rarely exceeds 10 feet. Areas of deposits subject to periodic flooding.	ALLUVIUM	Minor, thin deposits, possibly useful for dug wells, especially in coarse deposits of upland valleys.
Good foundation for light structures. Easily excavated, steeply sloping parts may be unstable if disturbed. Thickness [illegible] maximum 100 ft. Sinkholes [illegible] in thinner parts.	COLLUVIUM	Permeable, unconsolidated rock, some potential for screened wells in areas of thick deposits.
Excellent foundation material; removal requires blasting and heavy power equipment; will stand vertically in high cuts. Very low permeability, joints are vertical but highly irregular. Less than 6' soil cover.	DIABASE	Topographic low areas are the best places to drill; wells should not be drilled deeper than 150 feet; yields up to 10 gpm may be expected.
Good to excellent foundation material, difficult to excavate and removal requires blasting and heavy power equipment. Rocks exposed to elements disintegrate rapidly. Moderately permeable, seepage along fractures. Jointing not pronounced, sandstones and conglomerates are thick bedded. Soil cover ranges from 6" to 12".	HAMMER CREEK	Topographic low areas are the best sites for wells; most wells in this formation range in yield from 85 to 460 gpm; maximum yields obtained from wells drilled to 400 feet deep. Poor yields in metamorphic zone.
Fair to good foundation material, highly fractured, strong cleavage and very abundant joints in shales, fractures more widely spaced in sandy rocks and limestone. Weathered material easily excavated and may be thick, unweathered shales are moderately hard to excavate, conglomerate (Oh7) and especially sandy rocks (Oh3a and 3b) are particularly difficult, but are of minor extent. Natural slopes are stable with respect to rapid land movements, but may have a thick surficial creep zone. Some development of solution cavities and sinkholes in limestone (Oh6), low permeability, seepage along fractures.	HAMBURG SEQUENCE and MARTINSBURG	Substantial yields may be obtained from limestones (Oh6), upland stream valleys have best yields in other rocks, usually from zones greater than 200 feet in depth. Yields to 50 gpm may be obtained in shales and sandstones, but values near 10 gpm are typical.
Fair foundation material for light or medium structures. Moderately easy to excavate except conglomerate zone in lower Ohy. Two right angle joint sets, close to moderately spaced. Thin bedded and intensely cleaved. Soil cover usually less than 5 feet. Low permeability, seepage along joints.	HERSHEY and JACKSONBURG	Poorly permeable aquifer. Median specific capacity of wells is 0.4 gpm per foot of drawdown. Domestic supplies only.
Good foundation for light to medium structures. Moderately easy to excavate if weathered, blasting required at depth. Thin to medium bedded with carbonaceous partings giving high rate of seepage. Moderately jointed, sometimes cleaved. Low permeability, seepage on joints. Soil cover usually thin, occasional small sinkhole development.	MYERSTOWN	Poorly permeable aquifer but slightly more permeable than Hershey Limestone; domestic supplies only.
Good to excellent foundation material where sinkholes are few and far between. Difficult to excavate, requires blasting and heavy power equipment, will stand in vertical or near vertical cuts. Three well-developed joint sets, two at right angles and one oblique. Beds are massive in thickness. Soil cover up to 30 feet thick, sinkholes are numerous.	ONTELAUNEE	Generally highly permeable aquifer; median well yields in the 140 gpm range. Industrial and public supplies.
Good to excellent foundation material. Difficult to excavate, requires blasting and heavy power equipment, will stand in moderately steep cuts. Joints not pronounced; beds vary widely in thickness. Soil cover is thick (10' to 50'). Pinnacles exist on the bedrock surface, sinkholes are numerous.	EPLER	Typically poorly permeable aquifer. Well yields in the 30 gpm range. Domestic supplies only.
Excellent to good foundation material. Sinkholes less numerous than in other carbonate formations. Difficult to excavate, removal requires blasting and heavy power equipment, rocks will stand in vertical or near vertical cuts. Low permeability, seepage along fractures. Two right-angle joint sets moderately well defined. Beds are massive in thickness. Bedrock surface shows pinnacle weathering. Soil thickness ranges from several feet to over 30 feet.	RICHLAND	Typically poorly permeable aquifer but more permeable near contact with Millbach Fm. Well yields in the 50 gpm range. Domestic supplies only.
Good to excellent foundation material where sinkholes are few and far between. Difficult to excavate, requires blasting and heavy power equipment, will stand in vertical or near vertical cuts. Three well-developed joint sets, two at right angles and one oblique. Beds are massive in thickness. Soil cover up to 30 feet thick, sinkholes numerous.	MILLBACH	Highly permeable aquifer. Median well yields in 225 gpm range. Industrial and public supplies.
Good to excellent foundation material where sinkholes are few and far between. Difficult to excavate, will require blasting and heavy power equipment; will stand in vertical or near vertical cuts. Three well-developed joint sets, two at right angles and one oblique. Beds are massive in thickness. Soil cover is up to 30 feet thick, sinkholes are numerous.	BUFFALO SPRINGS	Typically moderately permeable aquifer but less permeable where near contact with Triassic rocks. Suitable for domestic supplies in its limited area of exposure.
Good to excellent for foundations. Excavation difficult, drilling and blasting required except where locally extensively fractured and weathered. Rock stands well in very steep cuts. Thick-bedded with fairly wide-spaced, blocky jointing. Low to moderate permeability, mostly in fractures. Soil thin on upper slopes, debris mantle of variable thickness on lower slopes.	HARDYSTON	Fair aquifer yields, 20 gpm or more in 75% of the wells. Best yields are in valleys and fracture zones.
Good foundation material; dominantly granitic rock, resistant to weathering, usually requires blasting, but some rock types may have weathered zone for moderately easy excavation. Often poorly jointed, with very large blocks in mantle. Very low permeability; some fracture seepage. Variable thickness of debris mantle, thin on upper slopes.	GNEISS	Poorly permeable aquifers, maximum yields in fracture zones and valleys. Domestic supplies only.

WELL DEPTHS SHOULD NOT EXCEED 200 FEET

SYMBOLS

Contact
Dashed where approximately located; dotted where concealed

Thrust fault
Sawteeth on upper plate. Dashed where approximately located; dotted where concealed.

High-angle fault
Dotted where concealed. U, upthrown side; D, downthrown side.

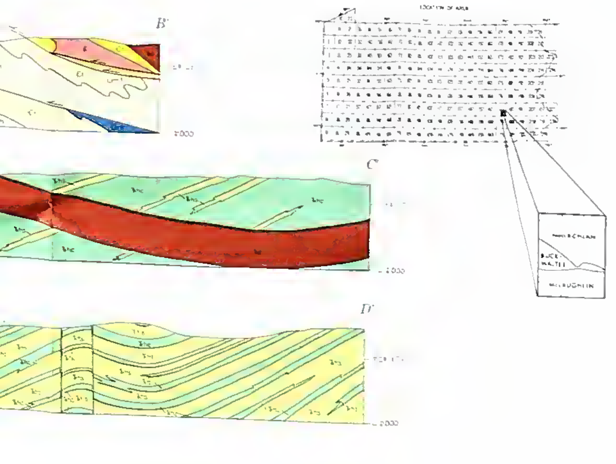
Inclined — Approximate
Vertical — Overturned
Strike and dip of beds

Active Quarry

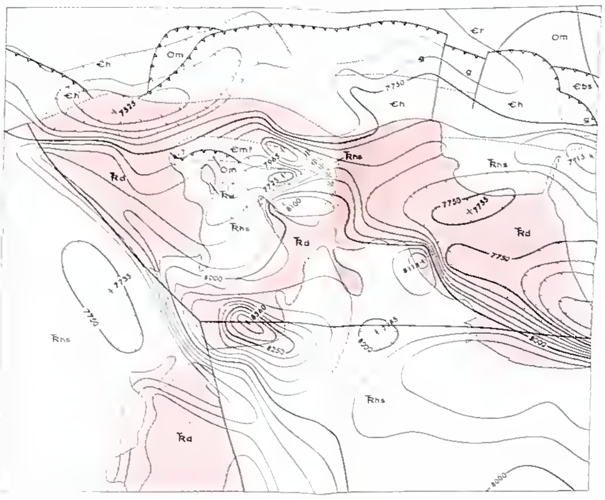
A — A′
Line of cross section

First cleavage (S₁) — Second cleavage (S₂)
Third cleavage (S₃)
Shale foliation, usually S₁ but may have transposed compositional layering parallel
Strike and dip of cleavage

Plunge of minor fold axis
Plunge of axes in closely folded strata
Plunge of overturned syncline axis
Plunge of overturned anticline axis



AEROMAGNETIC MAP OF THE WHEATFIELD AREA



Magnetic data from U.S. Geological Survey GP240

× Magnetic Iron Ore Mines
×¹ Ruth Mine - others Wheatfield Mines